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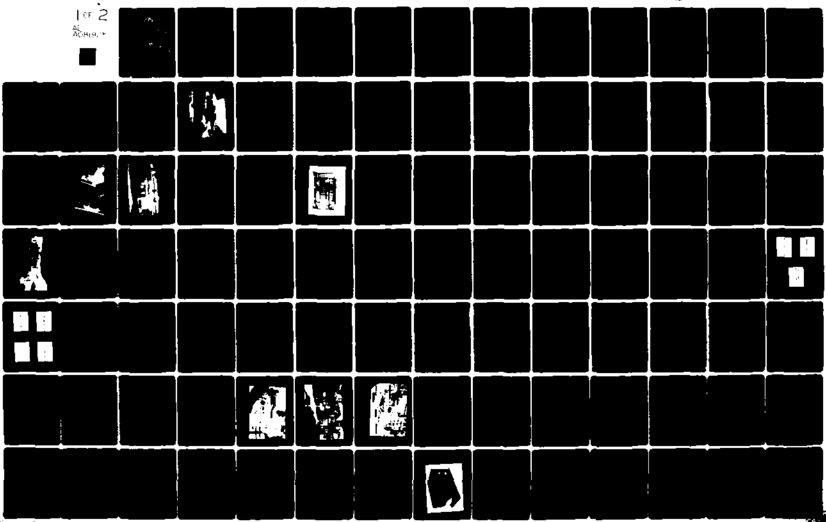

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FLIGHT VERIFICATION OF DIRECT DIGITAL DRIVE FOR AN ADVANCED FLIGHT CONTROL ACTUATION SYSTEM (AFCAS) IN THE T-2C AIRCRAFT

Rockwell International

North American Aircraft Division
4300 East Fifth Avenue
PO Box 1259
Columbus Ohio 43216

NOVEMBER 1979

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The feasibility of Direct Digital Drive for an Advanced Flight Control Actuation System (AFCAS) was successfully demonstrated in a T-2C aircraft. The test installation contained a digitally-controlled direct-drive rudder actuator, microcomputer, electronic drive unit, force transducers, and a localized 8000 PSI (55 MPa) hydraulic power supply. The system met all laboratory and flight test objectives and demonstrated direct microcomputer control of primary flight control surfaces. This program has demonstrated an approach that will improve performance and reliability of fly-by-wire control systems by reducing the system complexity.

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SUMMARY

This report describes a laboratory and flight test program that demonstrates a new concept for direct computer control for flight control surfaces. This is the sixth phase of a multi-phase program to develop an Advanced Flight Control Actuation System (AFCAS). In the digital AFCAS concept, computer processed signals are applied directly to primary surface actuators, eliminating traditional augmentation and secondary actuators. The actuator design employs a "building block" approach which standardizes various elements in the assembly.

The directional control system in a T-2C aircraft was changed to a full powered digital control-by-wire test installation. The T-2C rudder cable system operated a force transducer which converted pedal force to a proportional electrical signal. This command signal was transmitted to a microcomputer where it was summed with a feedback signal and processed to provide a pulse modulated command signal. The pulse modulated signal controlled a torque motor on the direct drive actuator.

Prior to flight testing, the complete rudder actuation system was tested in the laboratory. The laboratory testing included functional checks, dynamic testing, demonstration of the effects of various pulse modulation rates, and explored the performance characteristics of 6 to 12 bit resolution. In addition, self-monitoring features were programmed into the microcomputer which automatically returned the system to the analog backup mode if problems developed in the digital equipment. After the successful completion of the laboratory tests, the system was installed in the T-2C aircraft for flight testing.

The primary objective of the flight test program was to verify the feasibility of digital control of a direct drive actuator. The system flight test program was completely successful, with approximately 4.5 hours of flight time. Pilot comments were favorable, with the digital system producing satisfactory flight characteristics.

The feasibility of the digital AFCAS was successfully demonstrated. The microcomputer, actuator, and hydraulic system successfully completed all tests in the laboratory and in flight. This program has demonstrated an approach that will improve performance and reliability of fly-by-wire control systems by reducing the system complexity. The next logical step in the program would be the elimination of analog electronics, and the design and integration of digital electronics as part of the direct drive actuator.

PREFACE

This report documents research conducted by the North American Aircraft Division of Rockwell International Corporation, Columbus, Ohio, under Contract N62269-76-C-0201 with the Naval Air Development Center, Warminster, Pennsylvania. Technical direction was provided by Mr. C. Abrams, the Program Manager for Navy Flight Controls, (Code 60142).

This report discusses laboratory and flight testing of a direct drive surface actuator under the direct digital control of a microprocessor. The direct drive actuator is an 8000 PSI (55 MPa) unit in the yaw axis of a T-2C aircraft.

Acknowledgement is given to the following for participation on this project:

- Mr. W. Casey - Software Engineer
- Mr. W. Andrews - System Engineer
- Mr. R. Haning - Design Engineer
- Mr. D. Bomba - Chief, Flight Test Projects
- Mr. A. Lane - Test Pilot
- LCdr. R. Pierno - Navy Flight Representative

Appreciation is extended to the many individuals who provided helpful support and constructive criticism of the program; in particular Mr. C. Abrams, Mr. T. Jansen and Mr. W. Kaniuka of the Naval Air Development Center.

Discussions in this report of components and material supplied by various manufacturers shall not be construed as either an endorsement or criticism of any item. The Government incurs no liability or obligation to any supplier from the information presented herein.

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1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

The development of Advanced Flight Control Actuation Systems (AFCAS) for next generation aircraft has been a joint undertaking by the Navy and Rockwell International Corporation since 1972. This report presents the results of a laboratory and flight test evaluation of direct digital control of a primary flight control surface. A microcomputer controls actuation components developed in prior phases of the AFCAS program. This is the sixth phase of the AFCAS program.

The complexity of flight control systems has increased until present initial costs and required maintenance time are approaching prohibitive levels. This situation is due primarily to the design philosophy that improvements and refinements are best achieved by adding on accessories and/or components to proven, traditional systems. Broad new approaches and technologies involving advances in power generation, transmission, control, and actuation will be required to alleviate complexity in future Navy aircraft. The AFCAS Program is a significant step in this direction.

Phase I established that a direct-drive flow control valve, modular configured actuator, and a localized power package could be readily integrated into a computer-operated, fly-by-wire system. Adoption of AFCAS concepts should enhance flight control system maintainability, reliability, combat survivability, and lower initial costs, Reference 1.

Efforts to confirm the practicality of Phase I concepts were begun in Phase II with the design and fabrication of an engineering model, 8000 psi (55 MPa), control-by-wire, modular configured aircraft-type hydraulic servo actuator, Reference 2. Electrical inputs were applied to force (torque) motors employing cobalt samarium permanent magnets. Motor output was connected directly to single stage spool/sleeve type flow control valves. The force motors and flow control valves could be integrated into dual tandem, dual parallel, or single actuator configurations.

Phase III involved conducting laboratory performance tests on the engineering model actuator(s) built in Phase II, Reference 3. Static and dynamic tests were conducted on the force motors, motor/valve subassemblies, electronic drive unit, and actuator assemblies including dual system tandem, dual system parallel, and single system configurations. The dual tandem actuator was tested under load. Major achievements accomplished in Phase III were:

- Successful operation of a direct electrical control "muscle" actuator for primary flight control surfaces.

- Use of building-block elements to assemble dual tandem, dual parallel, and single actuator configurations.

- Successful operation of a control-by-wire hydraulic actuator, utilizing 8000 psi (55 MPa) operating pressure.

- Successful performance of a laboratory-type electronic drive unit which provided high immunity to circuitry failures.

In Phase IV, an 8000 psi (55 MPa) control-by-wire, modular rudder actuator was designed and fabricated for future flight testing on a T-2C airplane, Reference 4. Actuator design criteria were based on T-2C aerodynamic considerations, envelope constraints, and single system hydraulics. Actuator output was commanded by a single stage spool/sleeve valve driven directly by a permanent magnet force motor. The force motor was powered by an electronic drive unit which received inputs from a force transducer in the rudder system and position transducers on the actuator. A localized hydraulic power unit supplied 8000 psi (55 MPa) pressure for the rudder actuator.

In Phase V, a direct-drive control-by-wire muscle actuator, powered by a localized 8000 psi (55 MPa) hydraulic system, was used to control the directional flight of a T-2C, Reference 5. Successful operation of the test installation represented a significant milestone in the development of advanced flight controls. No problems were encountered; the system functioned exceptionally well and pilot response was favorable. The test results confirmed analyses and laboratory investigations reported in References 1 through 4. The ease with which flight testing was accomplished verified that AFCAS-type systems can be designed, fabricated and maintained without special techniques or state-of-the-art advances.

1.2 OBJECTIVE

The objective of Phase VI was to demonstrate that AFCAS-type actuators can be directly controlled by a digital computer. The computer control was demonstrated in system laboratory tests and in flight tests in a T-2C twin-engine turbojet trainer.

1.3 TECHNICAL APPROACH

The directional control system of a T-2C aircraft was changed to incorporate a full-powered Digital Fly-By-Wire (DFBW) mode with an Analog Back-Up(ABU) mode. The test installation contained:

- Hydraulic rudder actuator
- Localized hydraulic power unit
- Digital microcomputer
- Electronic drive unit (EDU)
- Associated sensors, wiring and power supplies

The original cable system between the rudder pedals and rudder was changed to incorporate the fly-by-wire test installation. The rudder pedal cables were attached to a sector which was prevented from rotating by a force transducer. Force on the pedals was converted to a proportional electrical signal from the transducer. This command signal was supplied to a microcomputer where it was summed with a feedback signal, and processed into a pulse width modulated (PWM) error signal. The PWM signal was power amplified in the EDU which powered the torque motor of a direct drive hydraulic rudder actuator. The modified system provided a microcomputer controlled, hydraulically powered rudder,instead of the manually operated rudder of the basic T-2C aircraft.

The hydraulic system, the direct drive actuator, the EDU, the LVDT actuator position feedback transducer, and the pedal force transducers were installed and flight tested in the T-2C during Phase V. This flight test program was reported in Reference 5. The Phase VI system was designed so that the signals from the transducers could be switched from the microcomputer unit directly into the EDU to provide an ABU mode with the same control capability as the Phase V flight system. The ABU mode could be selected manually, or selected automatically if the microcomputer monitor detected abnormal operation.

The safety provisions of the Phase V program were included in this phase. The direct-drive 8000 psi (55 MPa) rudder actuator,designed and fabricated in Phase IV,was equipped with a bypass valve. This device allowed the rudder to seek the trail position if system pressure were lost. In the event of a system failure, the pilot could permit the rudder to trail by turning the 8000 psi (55 MPa) supply "off".

All major components in the test installation were assembled in the laboratory for integration testing. System operation was verified in the laboratory prior to aircraft installation. Frequency response tests and temperature-altitude tests were performed simulating aircraft operation.

The test system was installed in a T-2C with instrumentation for electrical and hydraulic operation. Standard parameters such as air speed, altitude, engine rpm, etc., also were instrumented. Flight data were collected by photorecorder and telemetry systems.

Procedures were established for system checkout, ground demonstration, and flight testing. More than four and one-half hours of flight time were logged on the test system at various altitudes and airspeeds. Pilot observations and instrumentation data were used as a basis for evaluating the test system.

2.0 T-2C AIRPLANE

2.1 GENERAL DESCRIPTION

The T-2C "Buckeye" is built by Rockwell International Corporation, North American Aircraft Division-Columbus. The Buckeye is a two-place, subsonic trainer powered by twin turbojet engines. The aircraft is designed for both land and carrier based operations. Distinguishing features include wide-track tricycle landing gear, straight tapered wings, and low slung intake ducts, Figure 2-1.

The T-2C is equipped for cross-country flight, night flying and low altitude, high speed navigation exercises. Maximum level flight speed of the Buckeye is 465 knots (239 m/s) at 15,000 feet (4.6 km); the service ceiling is 45,000 feet (13.7 km). Takeoff and landing speeds are in the range of 95 to 110 knots (49 to 57 m/s). A typical takeoff gross weight is 13,000 pounds (5900 kg).

Dual power sources are provided for the electrical, hydraulic, and air-conditioning systems. The flight control system includes hydraulic full-powered ailerons, a boosted elevator, and an electric trim system; rudder operation is manual. The aileron and elevator actuators are part of mechanical linkage connecting the pilot's stick to the control surfaces. Thus, in the event of a hydraulic system malfunction, control of the aircraft can be accomplished manually.

2.2 HYDRAULIC SYSTEM

The T-2C has a 3000 psi (21 MPa), Type II (-65 to +275°F) (-54 to +135°C), single hydraulic system. Two pumps, one on each engine, provide power to operate the landing gear, speed brakes, arresting hook, aileron actuator, and elevator boost package. The pumps are constant pressure, variable delivery, axial piston designs. Each pump is capable of delivering 4.9 gpm (18.5 L/M) at 7800 rpm. Hydraulic fluid (MIL-H-5606) is supplied to the pumps by an air/oil type reservoir pressurized by engine bleed air. Fluid cleanliness is maintained by 5 micron absolute filters.

One pump can adequately handle all flow demands. However, if supply pressure should drop below 1800 psi (12 MPa), a priority valve is used to ensure operation of the aileron and elevator actuators. A cockpit controlled shutoff valve is installed in the aileron/elevator subsystem to permit simulating loss of power for training purposes. The landing gear and arresting hook can be lowered and locked by gravity, if desired. The wheel brakes have an independent hydraulic system.

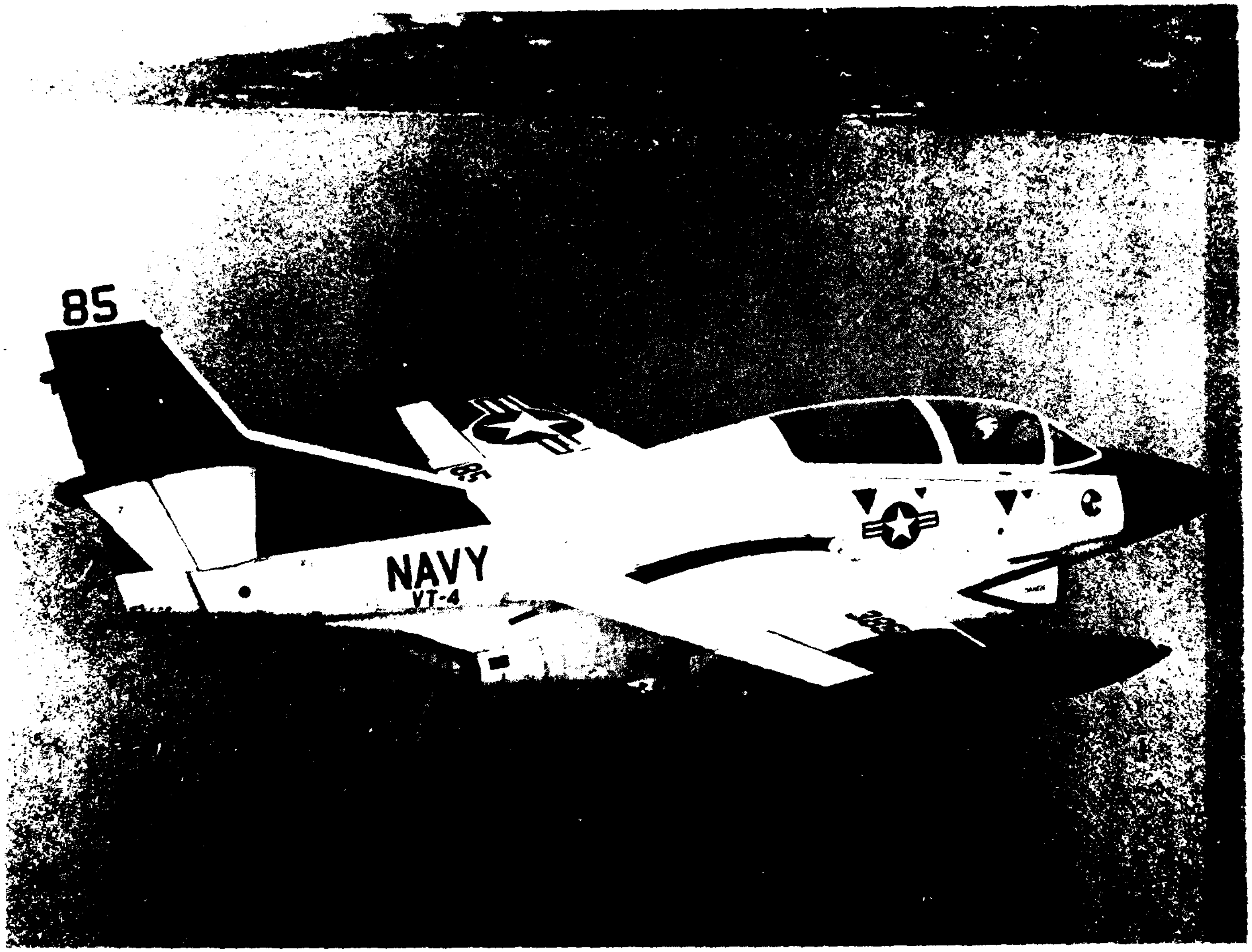


Figure 2-1 T-2C "Buckeye" Trainer

2.3 ELECTRICAL SYSTEM

Electrical power is supplied by two 28 volt DC, 300 ampere starter-generators, one mounted on each engine. The generators are connected for parallel operation and power the primary bus. Output voltages are regulated for varying loads and engine speeds.

Two nickel-cadmium 24 volt rechargeable batteries are used for engine starting and emergency DC power. The batteries are normally connected in parallel, but are used in series for engine starting.

A portion of the 28 volt DC power is converted to 115 volt 400 Hz AC power by two rotary inverters. Inverter No. 1 produces 500 volt-amperes for instruments; Inverter No. 2 supplies 1500 volt-amperes for avionics and serves as a backup source for instrument power.

3.0 AFCAS DIRECT DIGITAL DRIVE TEST INSTALLATION

3.1 GENERAL DESCRIPTION

The fly-by-wire rudder control system test installation,originally installed in the T-2C aircraft during Phase V of the AFCAS program and described in Reference 5, was modified to test a digital microcomputer generated PWM valve drive signal (Phase VI of the AFCAS program). Principal components in the test installation are:

- EDU - Localized Hydraulic Power Unit (8000 PSI) - Force Transducers - LVDT Position Transducers	Previously installed & tested per Phase V of the AFCAS program.
- Microcomputer Assembly - Microcomputer Power Supply	Installed and tested per Phase VI of the AFCAS program.

Two modes of system operation are provided, the DFBW mode and the ABU mode. In the DFBW mode, the microcomputer converts the pedal force command and rudder position feedback outputs into digital signals which are summed, amplified, and converted into PWM signals. The PWM signals are sent to each of two channels in the EDU where the signals are amplified and power converted into four torque motor PWM currents. In the ABU mode, the pedal force commands and rudder position feedback outputs bypass the microcomputer and are connected directly to the EDU where they are summed, amplified, and power converted into four torque motor currents.

Figure 3-1 shows a simplified block diagram of the T-2C Direct Digital Drive AFCAS test installation. Modifications incorporated in the T-2C for the previous Phase V AFCAS program and the subsequent Phase VI program (incorporation of a digital microcomputer to directly control the rudder actuator) are shown in Figure 3-2.

3.2 SYSTEM DESCRIPTION

Figure 3-3 shows a functional schematic of the system. The DFBW engage/ disengage functions are implemented by a cockpit control switch located adjacent to the AFCAS power switch on the Pilot's Auxiliary Instrument Control Panel. After the AFCAS analog system has been engaged, DFBW control will be selected by momentarily holding the DFBW engage switch to "ON". The DFBW control relays will energize to switch the transducer outputs to the microcomputer, and connect the microcomputer output to the EDU. When the microcomputer functions are operating correctly, a +28 volt DC power ground will be supplied to the holding coil of the cockpit DFBW engage switch. Disengagement of DFBW control will result from the following: manually selecting the DFBW engage switch to "OFF", automatically by the loss of the microcomputer supplied ground, or by manually selecting the AFCAS power switch to "OFF".

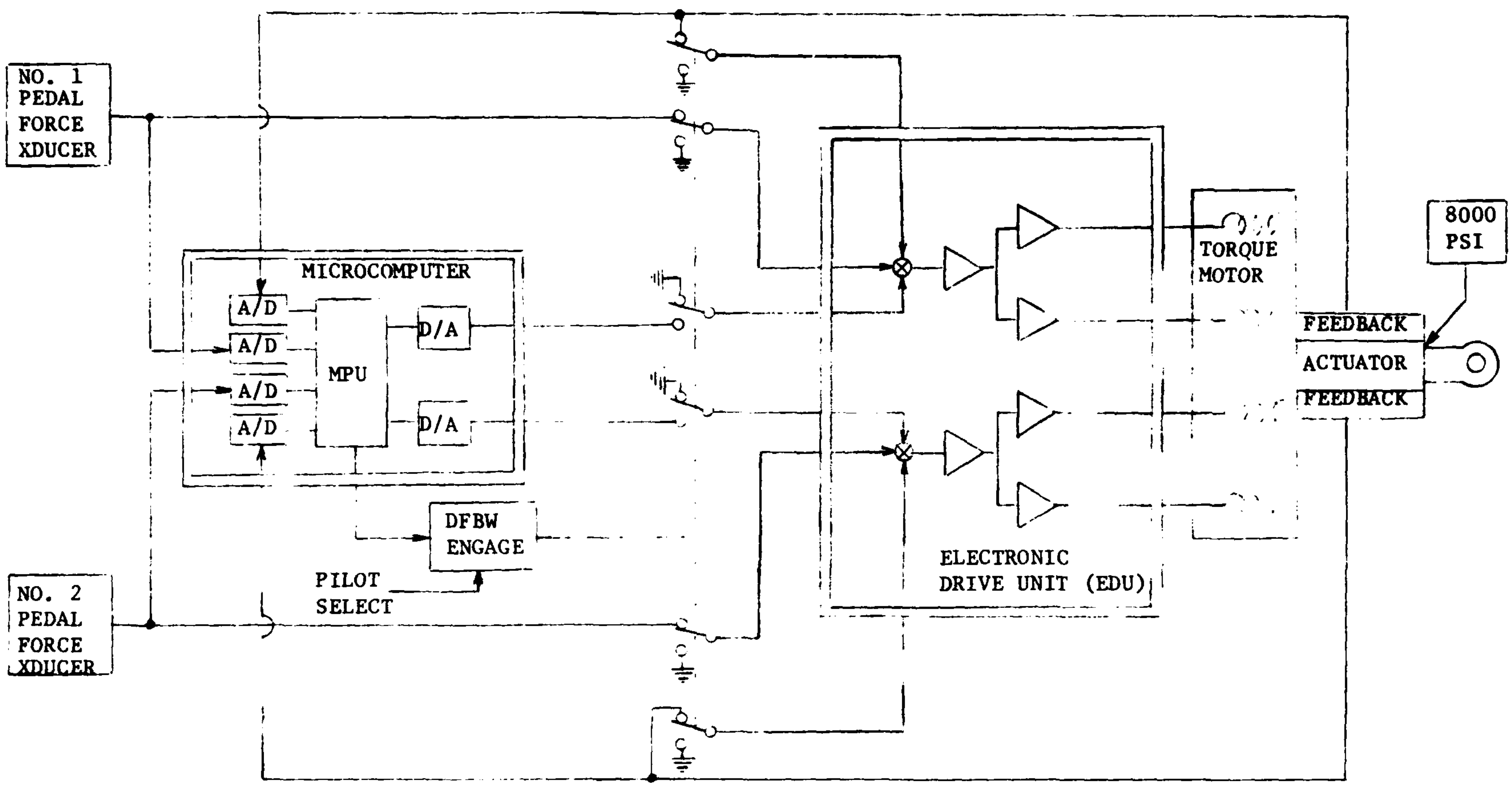
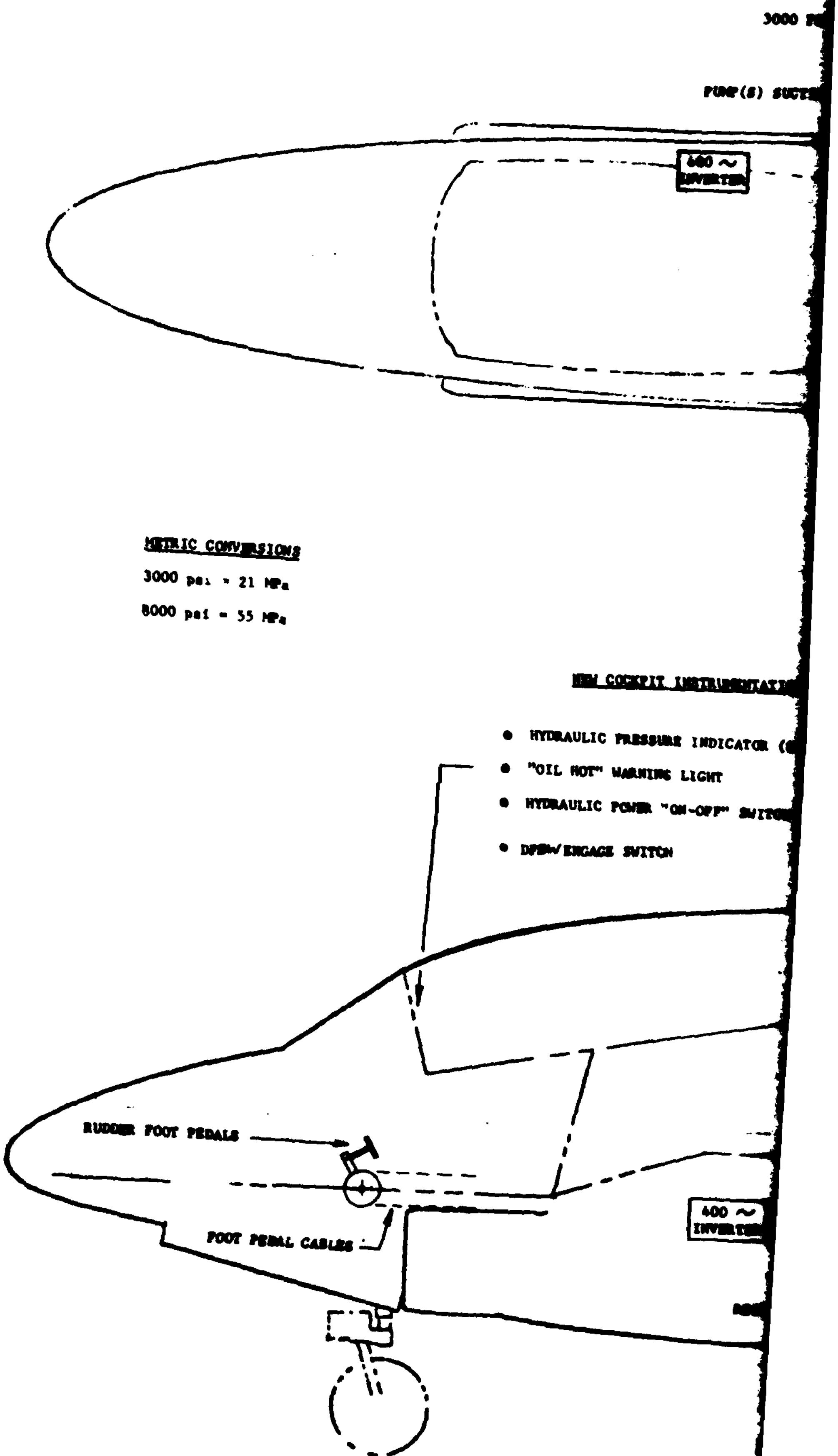


Figure 3-1 Simplified Block Diagram of T-2C AFCAS Direct Digital Drive Test Installation


3000 P
PUMP(S) SUCT
400 ~ INVERTER
METRIC CONVERSIONS
3000 psi = 21 MPa
8000 psi = 55 MPa
NEW COCKPIT INSTRUMENTAT
• HYDRAULIC PRESSURE INDICATOR (
• "OIL HOT" WARNING LIGHT
• HYDRAULIC POWER "ON-OFF" SWITC
• DFBW/ENGAGE SWITCH
RUDDER FOOT PEDALS
FOOT PEDAL CABLES
400 ~ INVERTER

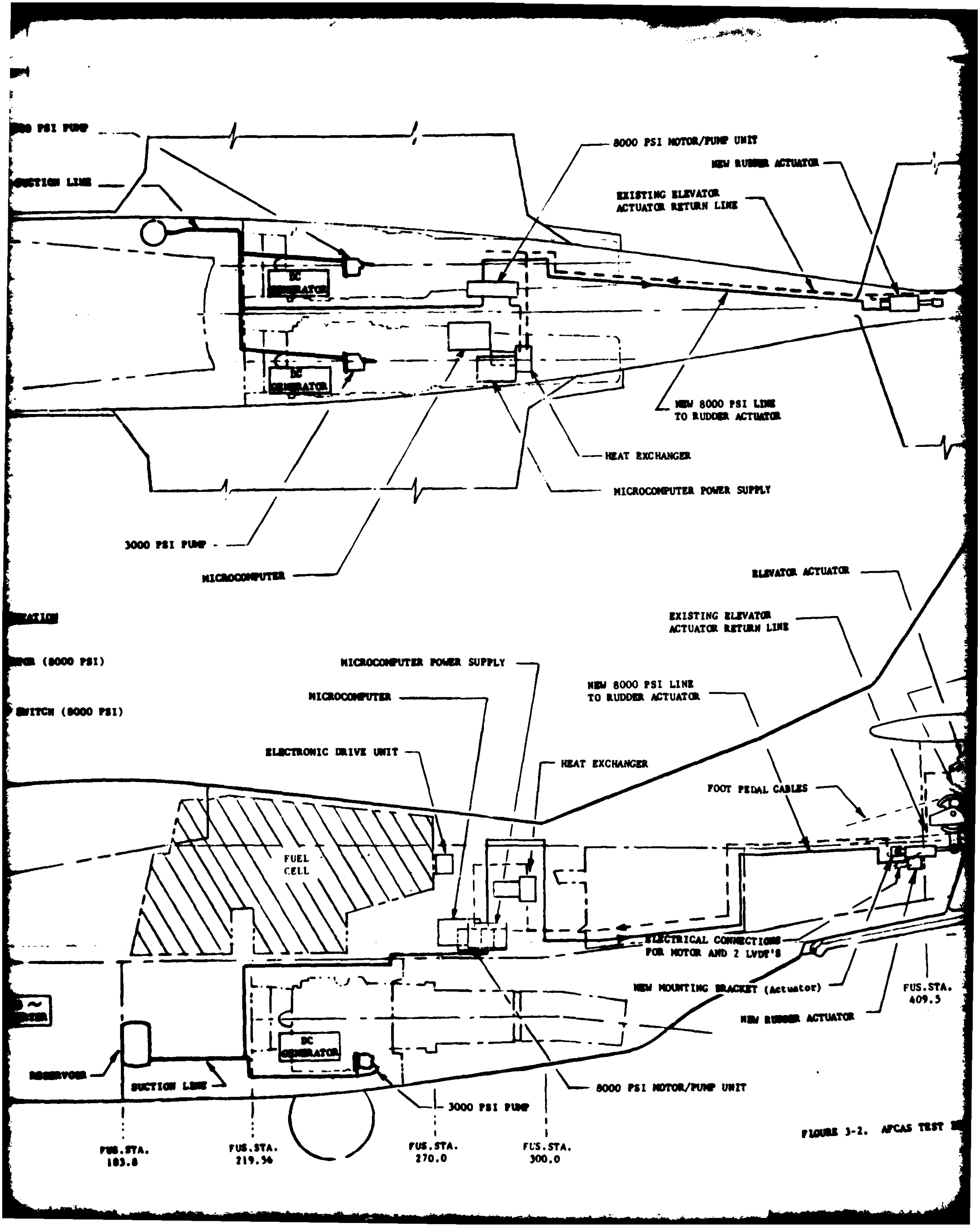


FIGURE 3-2. APCAS TEST

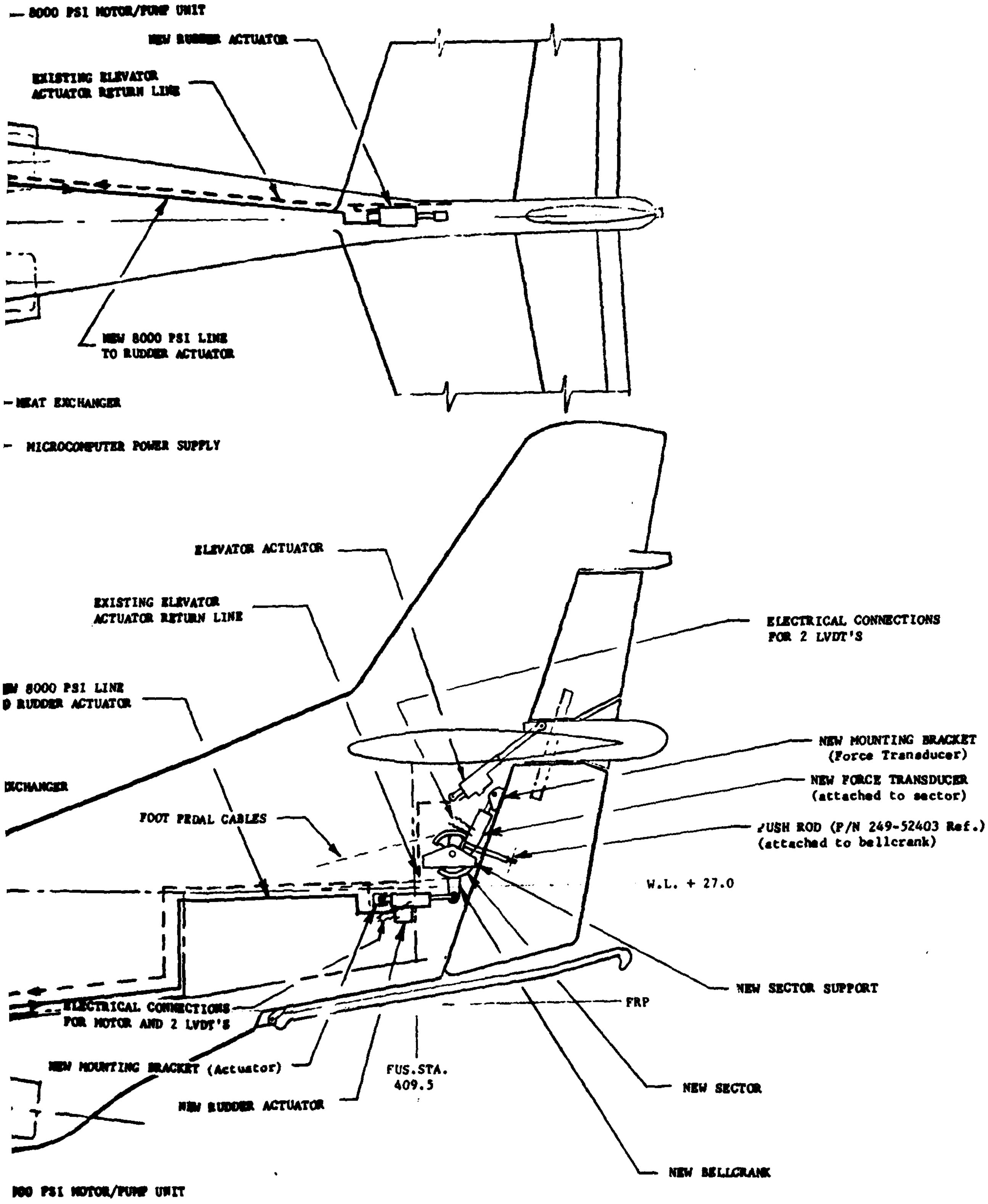
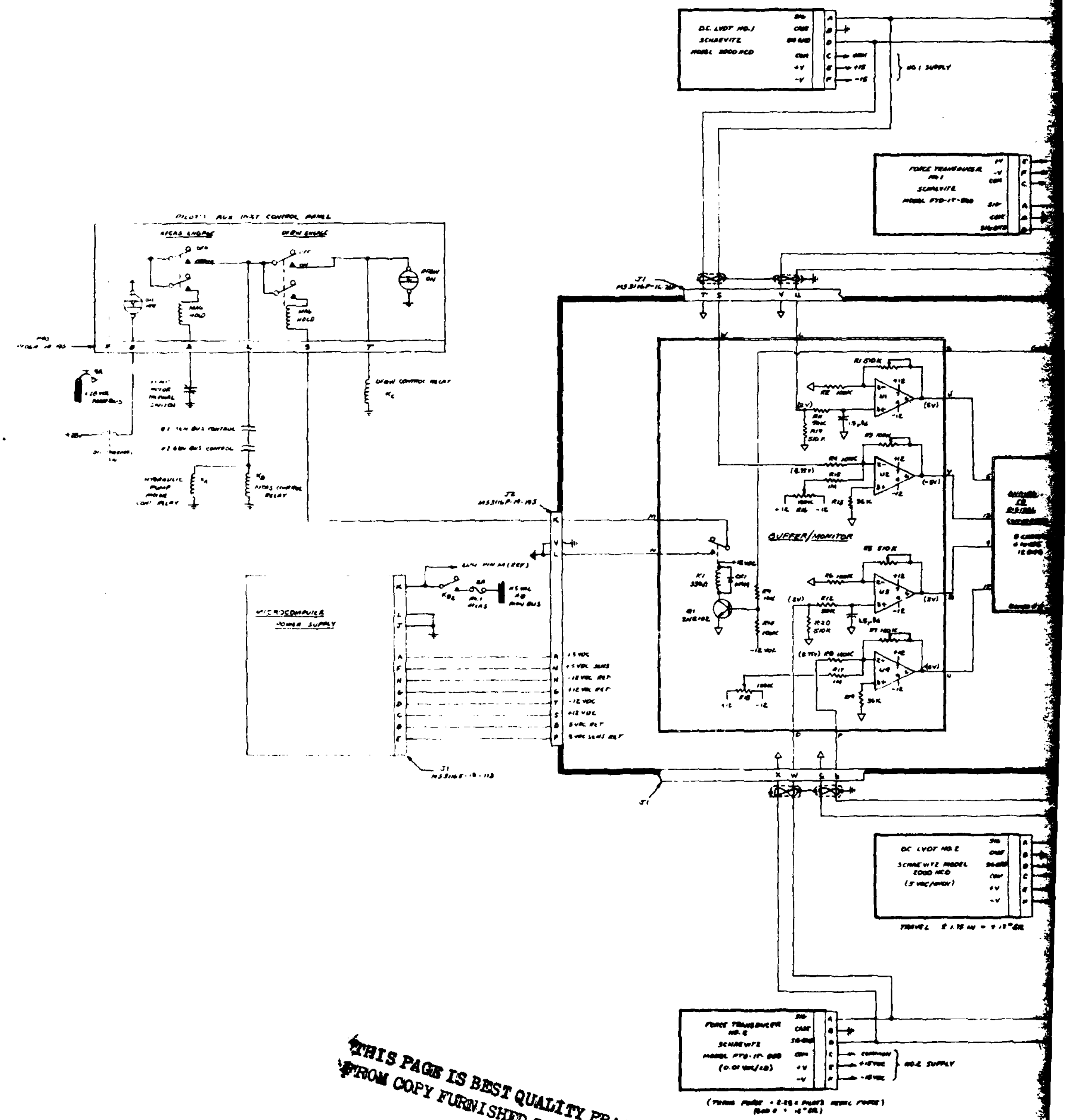
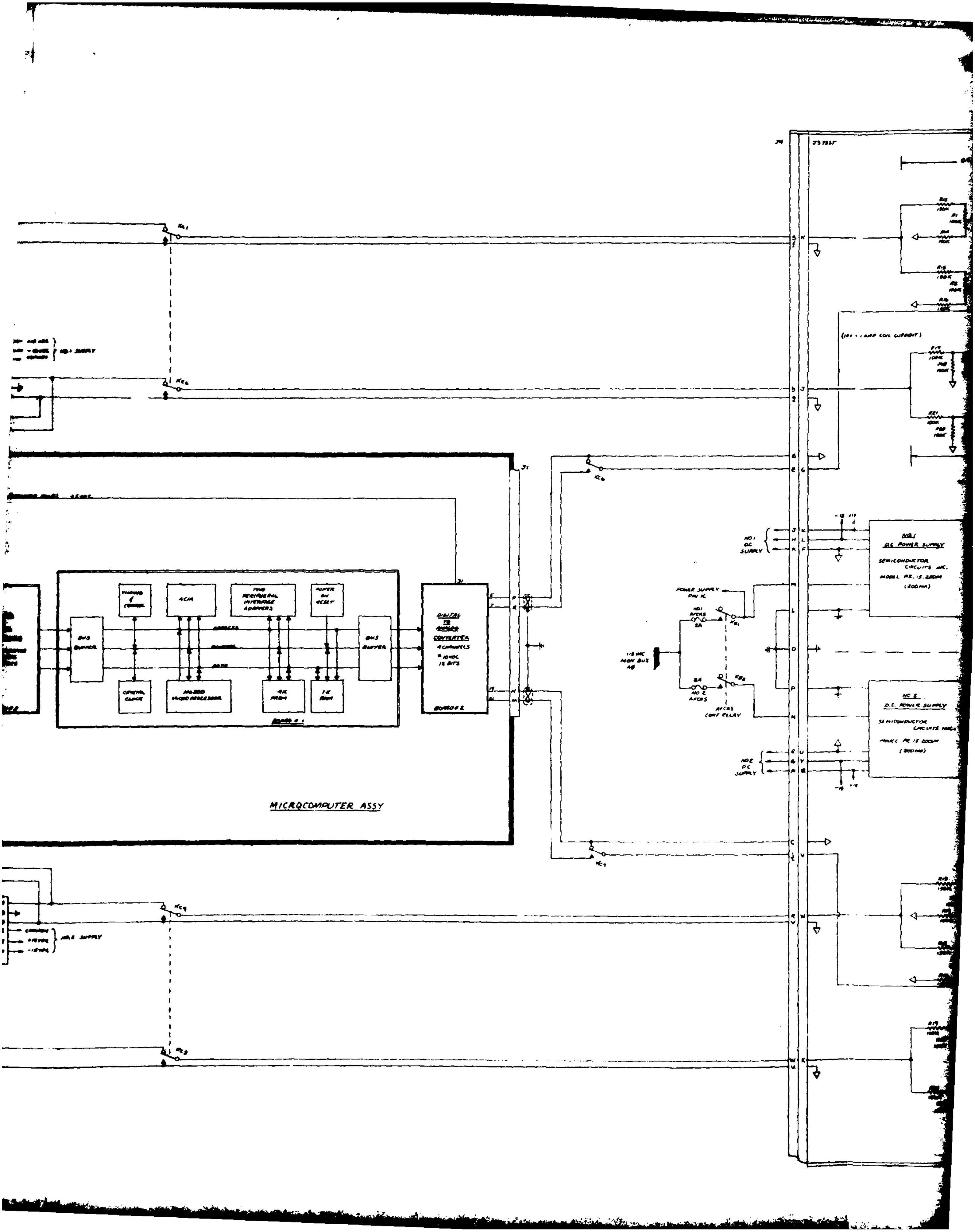
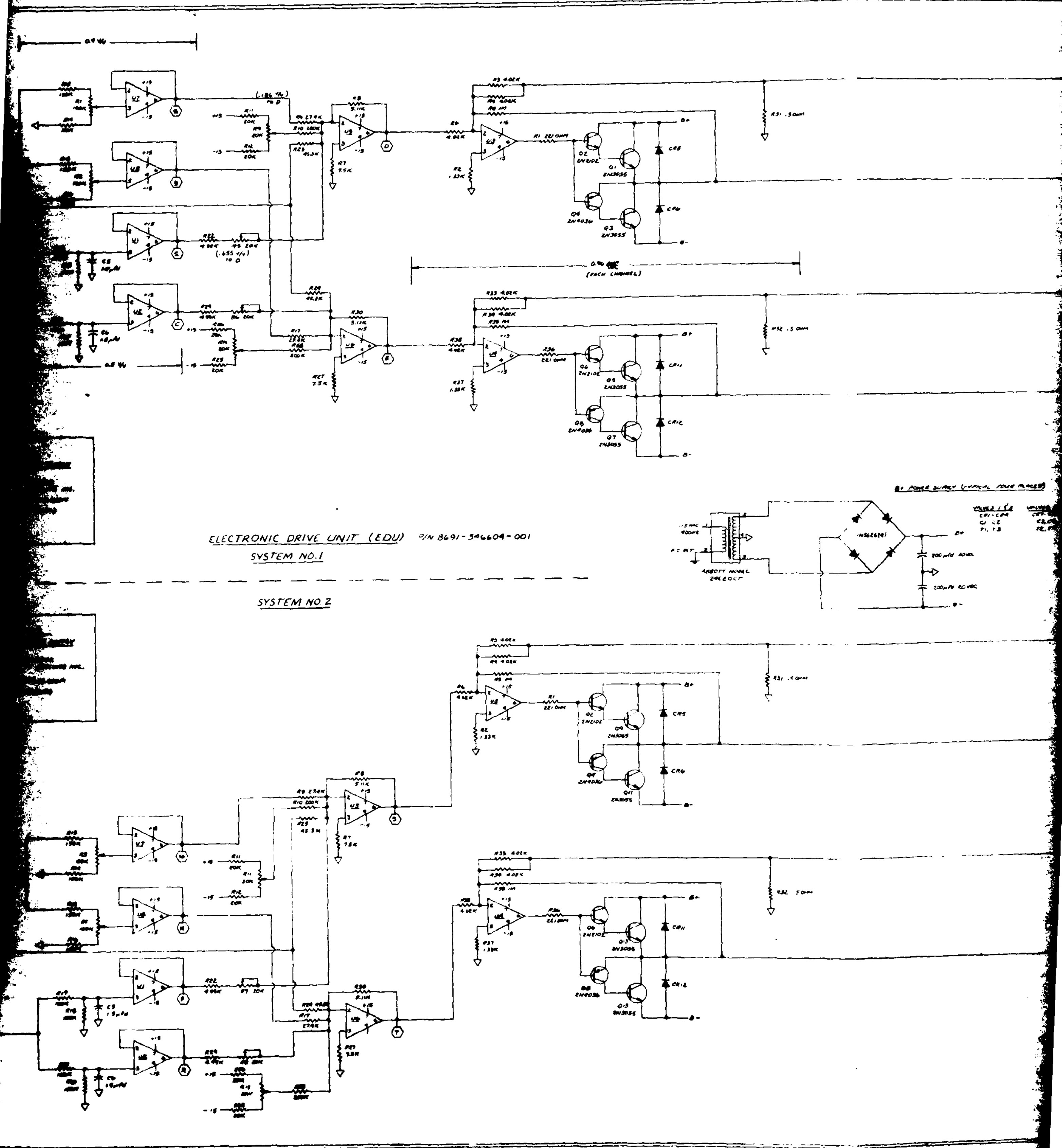


FIGURE 3-2. AFCAS TEST INSTALLATION WITH DIRECT DIGITAL DRIVE CAPABILITY


DC LVDT NO. 1
SCHAEVITZ
NO. 1 SUPPLY
FORCE TRANSDUCER NO. 1
SCHAEVITZ
PILOT'S AUX INST CONTROL PANEL
BUFFER/MONITOR
MICROCOMPUTER POWER SUPPLY
DC LVDT NO. 2
FORCE TRANSDUCER NO. 2
SCHAEVITZ
NO. 2 SUPPLY



MICROCOMPUTER ASSY
BUS BUFFER
BUS BUFFER
ACIA
CRYSTAL CLOCK
4K PROM
1K RAM
POWER ON RESET
BOARD # 1
NO 1 DC SUPPLY
NO 1 D.C. POWER SUPPLY
POWER SUPPLY PIN K
AFCAS CONT RELAY
NO 2 D.C. POWER SUPPLY
NO 2 DC SUPPLY


ELECTRONIC DRIVE UNIT (EDU) P/N 8691-546604-001
SYSTEM NO.1
SYSTEM NO 2

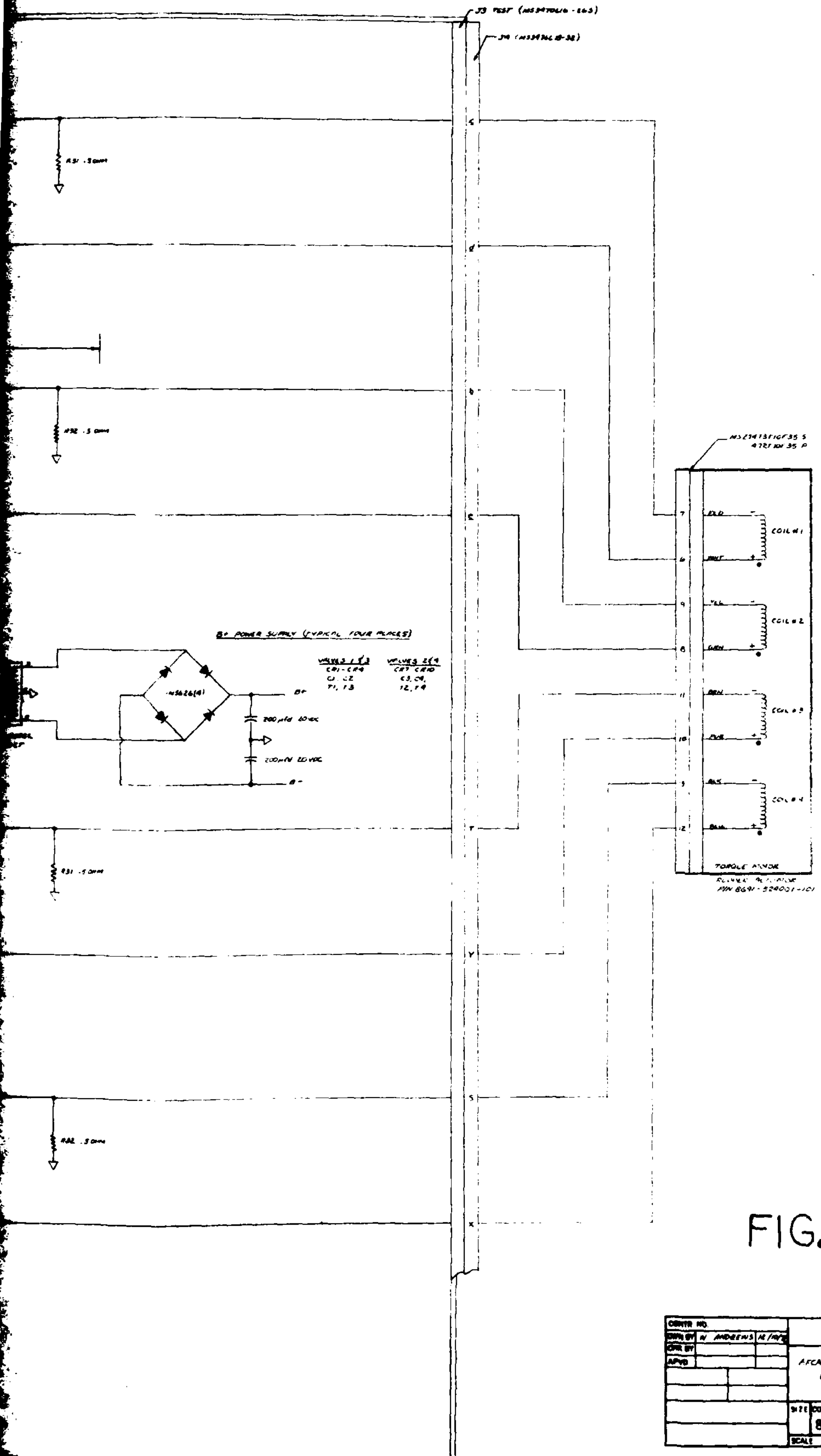


FIG. 3-3

CONTR NO.		Columbus Aircraft Division North American Rockwell	
DWN BY	N. ANDREWS		
CHK BY		AFCAS DIRECT DIGITAL DRIVE T2-C (INSTALL SCHEMATIC)	
APVD			
SIZE	CODE IDENT NO. 89372	INFORMATION PRINT	
SCALE			SHEET

FORM 300-T REV 11-70

3.3 ELECTRONIC DRIVE UNIT

The EDU shown in Figure 3-4 contains the electronics for sensor signal conditioning, signal summation, and power amplification to current drive the torque motor. The unit was designed and fabricated by the North American Aircraft Division-Columbus (NAAD-C). It is composed of two independent channels, each subdivided into dual valve driver circuits. A functional schematic of the EDU electronics is included in Figure 3-3. Each of the four power amplifiers employs current feedback with a highly reliable "Darlington" power transistor configuration. Redundant power supplies are used. The circuitry is designed so that in the event an output stage fails "hardover", the voltage applied to a motor coil will not exceed its rated value. This limiting feature permits a subunit failure to be compensated or nullified by another subunit. Closed loop tests showed that operation of the redundant subunits provided high immunity to component failures as reported in Reference 3, NR75H-1 Control by Wire Modular Actuator Tests (AFCAS).

3.4 PEDAL FORCE TRANSDUCERS

Two force transducers, Schaevitz Model FTD-IT-500, are used to convert pedal forces into DC signals. Excitation is provided by the EDU ± 15 VDC power supplies. The force transducers are connected to the pedals through a cable/sector assembly having a mechanical advantage of 2.28 (pedal force x 2.28 = transducer force). The transducers have a maximum capacity of 500 lbs. (2.2 kN), a spring rate of approximately 8000 lb/in (1.4 MN/m), and a design scale factor of 0.01 v/lb (.002 v/N).

The pedal force transducer assembly is shown in Figure 3-5.

3.5 ACTUATOR POSITION TRANSDUCERS

Two Schaevitz Model 2000 HCD DC Linear Variable Differential Transformers (LVDT's) provide dual position rudder actuator feedback signals. Excitation is provided by the EDU ± 15 VDC power supply.

Actuator position travel, ± 1.75 in. (±4.45 cm) max., is converted through a bellcrank and push rod to angular travel of the rudder, ±12° max. The design scale factor for both LVDT's is 5.0 VDC/inch (1.97 VDC/cm).

The position transducers are shown mounted on the rudder actuator in Figure 3-6.

3.6 AFCAS ACTUATOR

The fly-by-wire AFCAS rudder actuator, P/N 8691-524001-101, is directly driven by a permanent magnet force motor having four independent coils for redundancy. The force motor armature is mechanically coupled to a spool/sleeve flow control valve which commands actuator piston rate. Piston feedback is provided by dual DC LVDT's mounted externally on

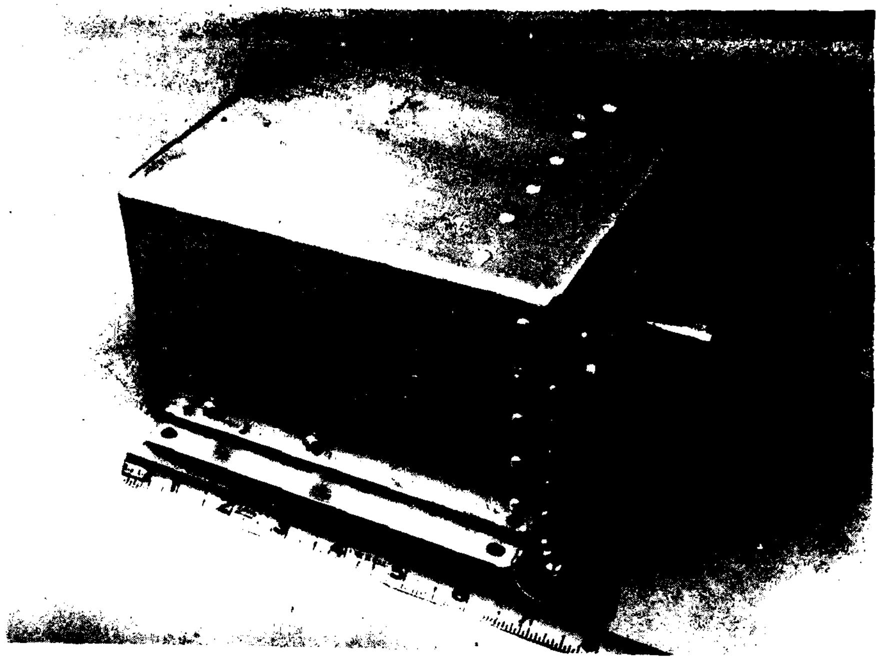


Figure 3-4 Electronic Drive Unit

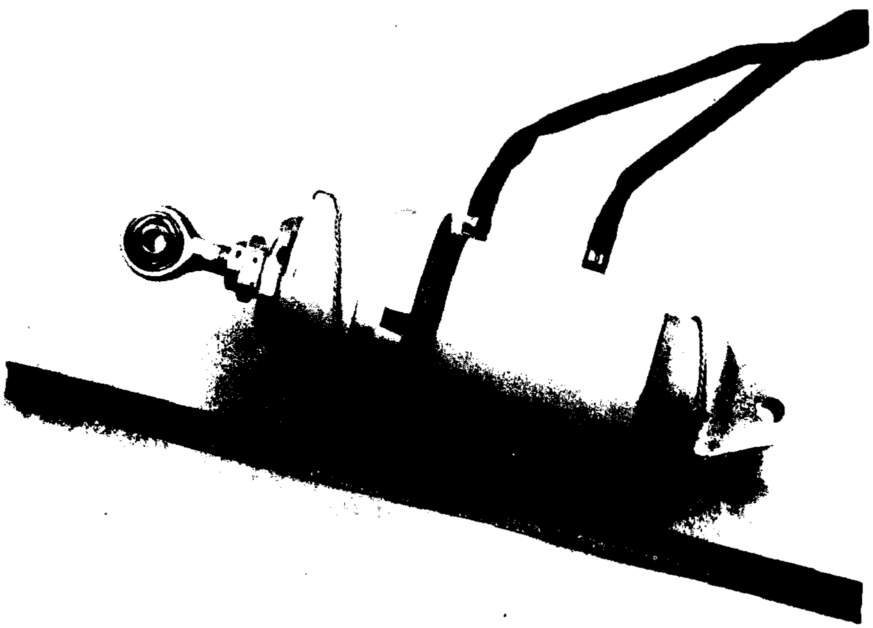


Figure 3-5 Force Transducer

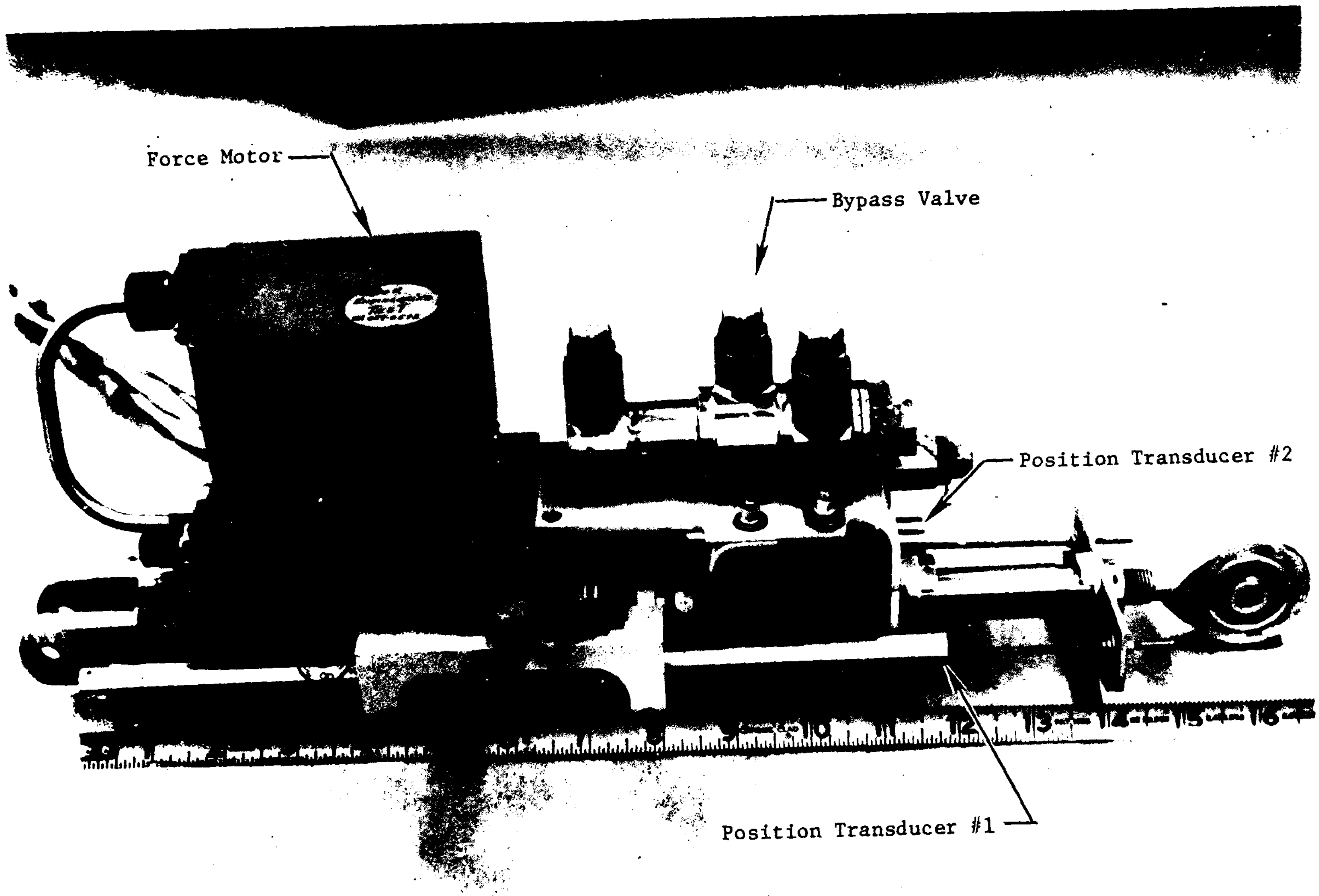


Figure 3-6 Rudder Actuator Assembly

opposite sides of the actuator housing. A hydraulic bypass valve was added to automatically interconnect the two cylinder chambers in the event hydraulic power were lost. The T-2C rudder has a travel of ±25°. For safety reasons, rudder travel was reduced to ±12° in the test installation by limiting actuator stroke. This permits the pilot to land safely with a "hard-over" rudder, opposite engine out, and three knot cross-wind.

Actuator constants are listed below:

Operating Pressure	8000 psi (55 MPa)
Piston Stroke (total)	3.5 In. (8.9 cm)
Cylinder Bore	0.926 In. (2.3 cm)
Rod Diameter	0.748 In. (1.9 cm)
Piston Effective Area	0.234 $In.^2$ (1.5 cm^2)
Force Output (Max.)	1870 Lb. (8.3 kN)
Piston Velocity (Max.)	5.5 In/Sec. (14 cm/s)
Actuator Length (Extended)	18.375 In. (46.7 cm)

Manufacturers and major components of the actuator were:

Part No.	Description	Manufacturer
8691-524001-101	Rudder Actuator Assembly	North American Aircraft Division-Columbus Plant, Rockwell International
8691-524001-051	Bypass Valve	" " "
SO 4262-03-21	Control Valve	Ronson Hydraulic Units Corporation Charlotte, North Carolina
99-D0234 (M/N 21-6-200)	Force Motor	Servotronics, Inc. Buffalo, New York
2000 HCD	Position Transducer	Schaevitz Engineering Camden, New Jersey

The actuator assembly is shown in Figure 3-6.

3.7 MICROCOMPUTER ASSEMBLY

The microcomputer assembly is housed in an enclosed unit, and consists of the following subassemblies:

Part No.	Nomenclature
M68MM01A	Motorola Mono-Board Microcomputer Module
M68MM05A	Analog-To-Digital (A/D) Converter Module
M68MM05C	Digital-To-Analog (D/A) Converter Module
M68MMCC05	Card Cage & Mother Board Assembly
EO H383246-11	Signal Conditioning Board

The mono-board microcomputer module is shown in Figure 3-7, and is a complete computer-on-a-board having all the processing and control required for a microcomputer-based system. It incorporates the MC 6800 MPU, 1 K of Random Access Memory (RAM), provisions for 4 K of Programmable Read Only Memory (PROM), timing and control, buffers, an Asychronous Interface Adapter (ACIA) and two Peripheral Interface Adapters (PIA).

The A/D converter module consists of eight channels of A/D conversion of which four are utilized. The D/A converter module consists of four channels of D/A conversion of which three are utilized.

The signal conditioning board contains four channels of sensor signal conditioning and a relay driver that interfaces the microcomputer monitor output with the system control logic.

Additional information on the microcomputer assembly is contained in Appendix A.

3.8 MICROCOMPUTER POWER SUPPLY

A separate power supply, Motorola P/N M68MMPS1, converts single-phase, 115 VAC, 400 HZ to + 5 VDC, and ± 12 VDC to power the microcomputer assembly.

3.9 SOFTWARE DESCRIPTION

3.9.1 Function

Software was developed to enable the microcomputer to perform two basic functions; a command/feedback control function and a control monitor function.

The command/feedback control function sums the pilot command and rudder position signals to produce an output signal proportional to the difference to drive the actuator.

The control monitor function measures the level of error between the pedal command and the rudder actuator position feedback, and if a preset level is exceeded for a given period of time, the engage command will be removed. Actuator control will then revert to the ABU mode. A continuous check is also made on the transducer input A/D conversion hardware by comparing the two digital feedback signals with each other and in a similar manner comparing the digital pedal signals. Any differences exceeding preset levels for a given period of time will result in switching system control to the ABU mode.

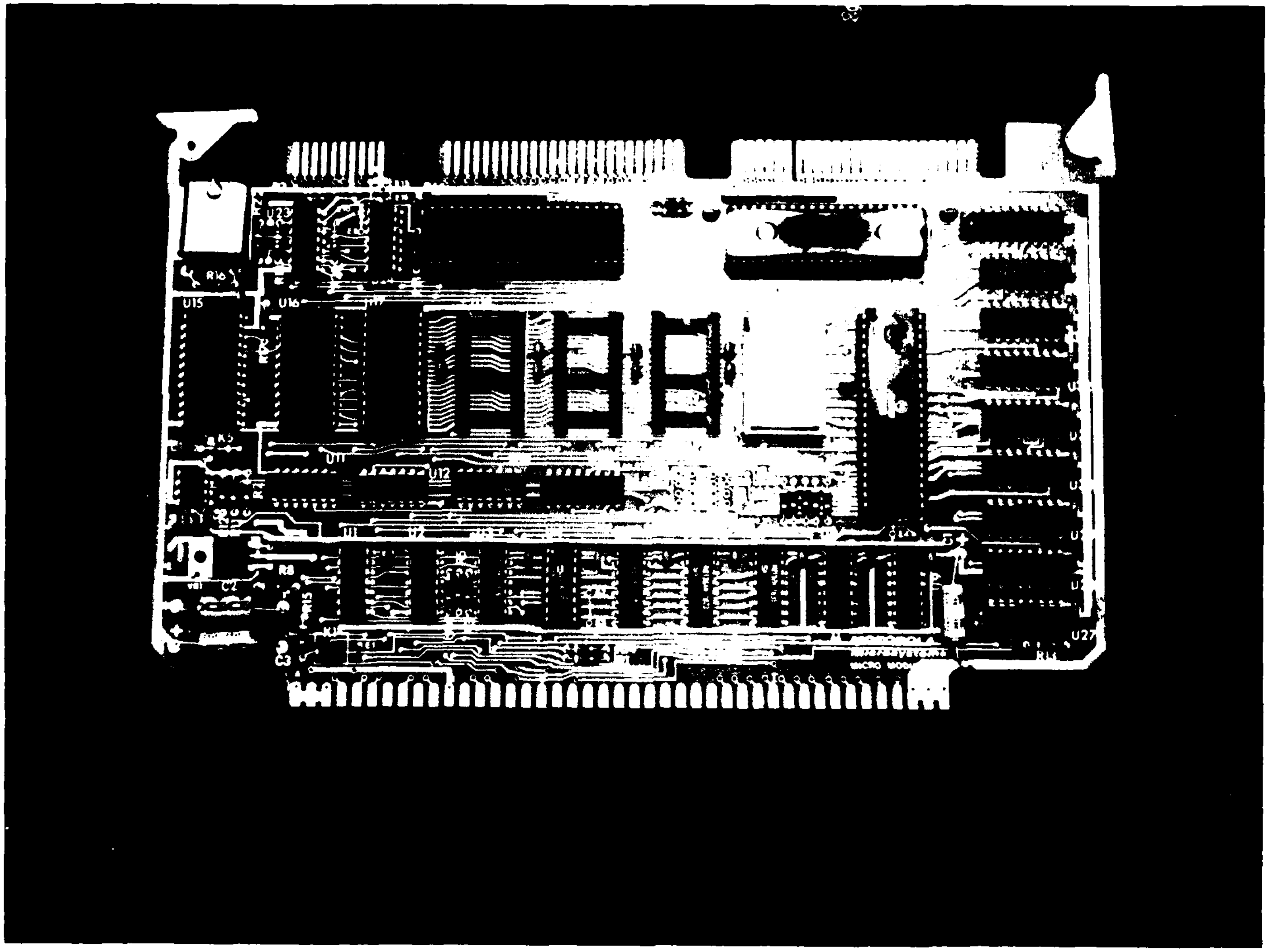


Figure 3-7 Motorola M68MM01A Microcomputer Monoboard Assembly

The control monitor function was incorporated as the Motorola microcomputer is a single channel device which could generate a "hardover" command under certain failure conditions. The dual-channel redundancy of the ABU mode prevents a "hardover" command of the rudder even if a pedal transducer or rudder position transducer fails in a "hardover" condition.

3.9.2 Program Modules

The DFBW Microcomputer Program Flow Chart, Figure 3-8, illustrates the modular nature of the software and the sequence in which the modules function. The program modules were designed, coded, and initially checked as individual entities prior to being integrated.

Following is a brief description of the program modules:

Initialize - The Initialize module sets the D/A Converter (DAC) channel 4 to provide +5 VDC to hold in relay K1 (ref. Figure 3-3). The K1 relay, in turn, holds the DFBW Engage switch in the engage position. This module also sets timing counters to ensure that the Monitor function does not immediately turn off the DFBW Engage switch.

Input 1 - The Input-1 module, as the first in the repetitive loop, is used to start the PWM output signals. This is done by setting both DAC-1 and DAC-2 at +10 VDC. It then controls the A/D conversions of pilot command (CMD1) and rudder position (POS1). Inputs are scaled so that full scale, $\pm 12°$ of rudder is ± 5 VDC, which is one-half of full range for the A/D channels. Since the force transducer that provides CMD1 is not mechanically or electrically limited to ± 5 VDC, a software limit is provided to set CMD1 at either ± 5 VDC, as appropriate, when that value is exceeded. Output of the A/D converter is a 12 bit word, proportional to the voltage.

Error - The error module performs a double precision subtract of CMD1 from POS1 and sets computer gain through a series of shifts. It then determines polarity of the error and transfers to the appropriate output module.

Output - The output module sets countdown timers that establish the duration of the plus and minus portions of the PWM output signal. It switches DAC-1 and DAC-2 to -10 VDC when the "positive" counters have timed-out. When the "minus" counters time-out, it transfers control to the Input 2 module.

Input 2 - The Input 2 module controls the conversion of CMD2 and POS2 and provides limits on CMD2 in the same manner as Input 1. CMD2 and POS2 are for use in the Monitor functions.

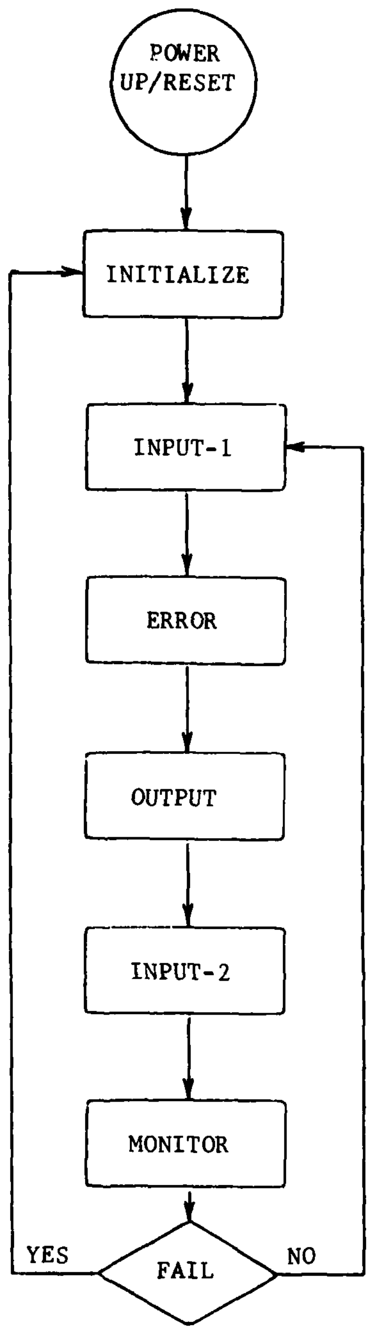


Figure 3-8 Digital Fly-By-Wire Microcomputer Program Flow Chart

Monitor - The Monitor module compares the redundant pilot command and rudder position input signals. If a difference in either of 1.5° is detected for a period of 0.128 seconds, the program is set to deenergize the DFBW holding relay (K1 in Figure 3-3) and reverts control of the system into the ABU mode. The monitor also checks the magnitude of the error signal. If it exceeds 1.5° for 2 seconds, the DFBW holding relay is deenergized, and control of the system again reverts to the ABU mode. As long as the monitor does not detect an error, it transfers control back to the Input 1 module.

3.9.3 Flight Test Program Software

Support software, trade name "Microbug ROM" was purchased with the microcomputer equipment and enabled communications with the microcomputer via a Teletype Corp. Model 33TU teletype keyboard/printer reader/punch unit. An RS-232-TO-TTY adapter unit provided the interface through the ACIA, between the microcomputer and the teletype.

The communication consisted of entering both program and simulated input data, monitoring microcomputer operation, and dumping of programs onto paper tape for storage.

After the software modules were operating satisfactorily they were then merged to become an operational program. After checking the operational program with the microcomputer integrated into the rudder system (in the laboratory), the program was then loaded into a PROM. The PROM was installed in the microcomputer and the operational program verified. All subsequent final system response testing and calibration for the flight configuration was performed with this PROM installed in the microcomputer.

A listing of the flight program software is contained in Appendix B. The program was designed to function at a rate of 500 HZ, and occupies 462 bytes of the available 4096 bytes of PROM and 18 bytes of the 1024 bytes of "scratch pad" RAM. The PROM map is also contained in Appendix B.

3.9.4 Microcomputer Analog and Reduced Bit Resolution Program Software

In addition to the PROM software developed for the flight test program, additional software programs were developed to evaluate operation of the microcomputer as an analog device and to evaluate microcomputer performance as a function of reduced bit resolution and various PWM frequencies. These programs were designed for lab testing only, and were therefore stored on paper tape and entered into the microcomputer memory via the teletype.

3.10 HYDRAULIC SYSTEM

The hydraulic system remained unchanged from the previous Phase V of the AFCAS test program, described in Reference 5. Changes incorporated in the basic T-2C hydraulic system for the Phase V test program were:

- Addition of an electric motor driven 8000 psi (55 MPa) variable delivery pump.

- Addition of an 8000 psi (55 MPa) control-by-wire rudder actuator and bypass valve.

- Addition of a suction line from the reservoir to the 8000 psi (55 MPa) pump, pressure line from the pump to the rudder actuator, and actuator return line.

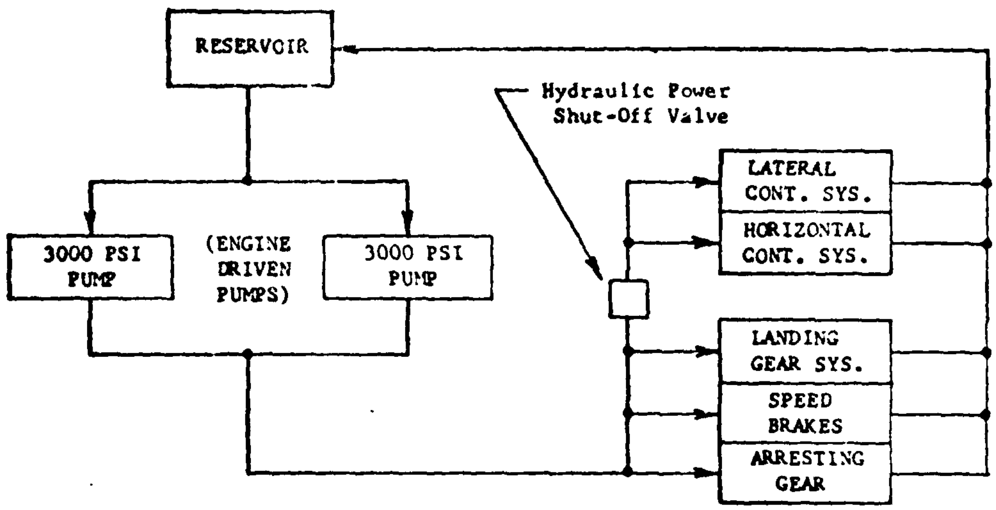
- Addition of pump case drain return and shaft seal overboard line.

- Relief valve installed in the 8000 psi (55 MPa) system.

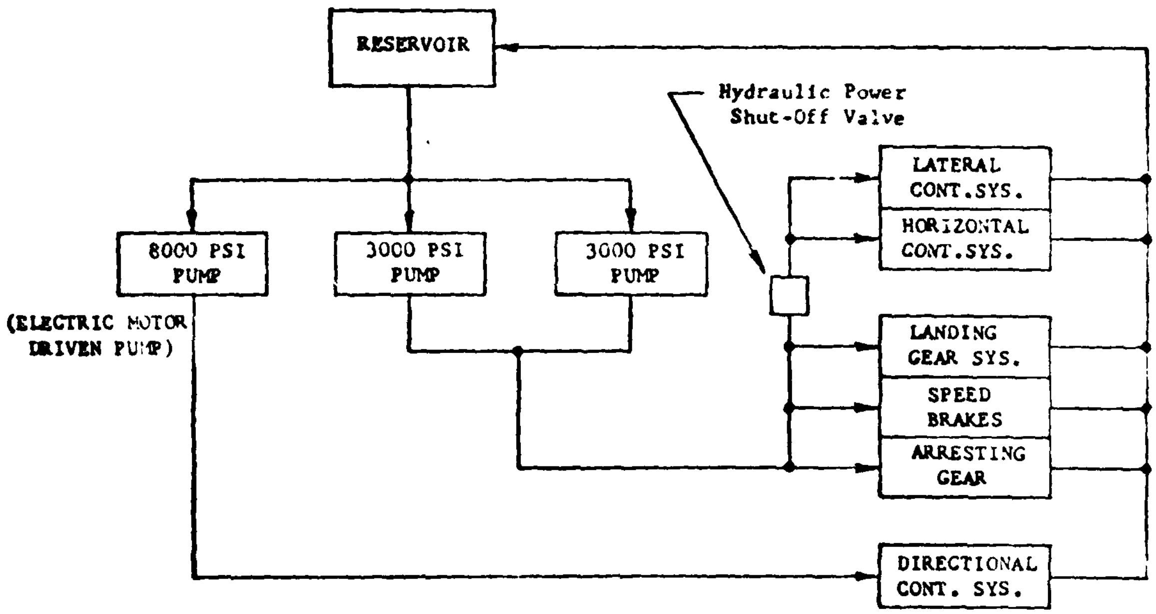
- Heat exchanger installed in the 8000 psi (55 MPa) pump case drain line.

The original and modified hydraulic systems are compared schematically in Figure 3-9.

The modified system is shown schematically on Figure 3-10; 8000 psi (55 MPa) components are listed on Table I. The 3000 psi (21 MPa) and 8000 psi (55 MPa) systems shared a common reservoir and common return lines. All major components, except for the rudder actuator, were located in the fuselage compartment above the engines.



ORIGINAL 3000 PSI SYSTEM



MODIFIED HYDRAULIC SYSTEM

Figure 3-9 Original and Modified Hydraulic Systems

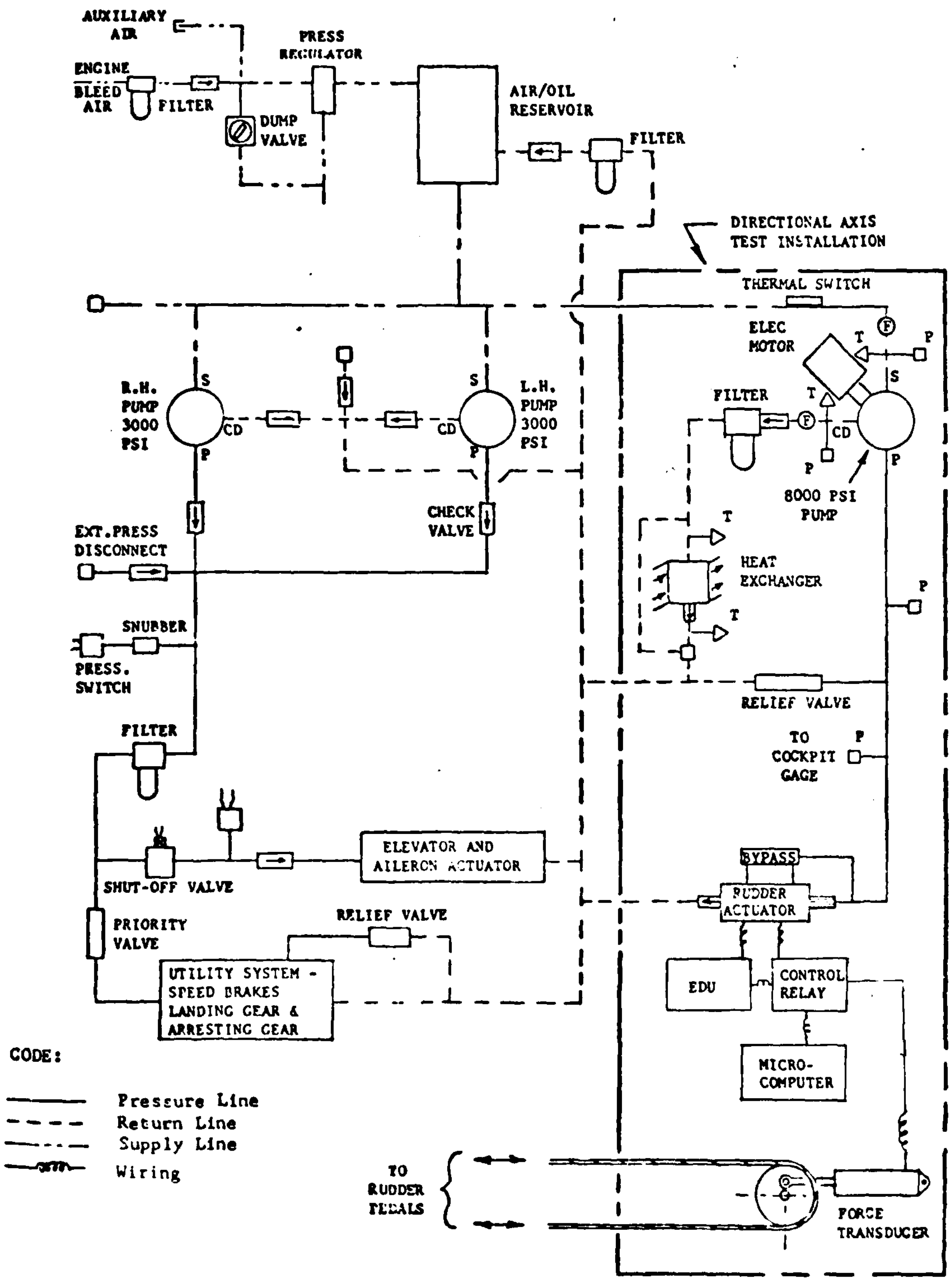


Figure 3-10 Schematic Diagram of Modified Hydraulic System

TABLE I

LIST OF 8000 PSI (55 MPa) COMPONENTS

PART NO.	DESCRIPTION	MANUFACTURER
66059	Motor/Pump Unit	Aerospace Division of Abex Corporation
		Aerospace Electrical Division of Westinghouse Electric Corporation
8691-524001-101	Rudder Actuator Assembly	North American Aircraft Division, Columbus Plant, Rockwell International Corporation
8691-524001-051	Bypass Valve	North American Aircraft Division, Columbus Plant, Rockwell International Corporation
1180A	Hydraulic Relief Valve	PneuDraulics, Inc.
R44598-6-0310	Hose	Resistoflex Corporation
21-6-9	Tubing	Trent Tube Division of Colt Industries
Dynatube® Series	Fittings	Resistoflex Corporation
MIL-H-83282	Fluid	Royal Lubricants Co.

® Dynatube, a Resistoflex development, is patented in the United States and foreign countries.

4.0 LABORATORY TESTS

4.1 TEST OBJECTIVES

Laboratory tests were performed to integrate the microcomputer into the existing Phase V AFCAS system, evaluate system performance and compatibility with the microcomputer operational modes and software, and to ensure the equipment would function properly in the T-2C aircraft environment prior to installation in the aircraft.

The DFBW and ABU system operating modes were evaluated in the laboratory. In the ABU mode, the microcomputer is disconnected from the loop, and the aircraft sensors directly control the actuator through the EDU. This was the control used in Phase V of this program. Laboratory testing was also accomplished with the microcomputer supplying an analog signal instead of a PWM signal to the EDU. This testing was performed to obtain comparison data with the computer in the loop.

4.2 TECHNICAL APPROACH

The actual aircraft hardware was used whenever possible in the lab test set-up to permit testing and evaluation of the flight hardware and to eliminate potential problems during subsequent installation and operation in the aircraft.

Included in the lab test set-up were the rudder LVDT feedback transducers, rudder actuator, EDU, microcomputer and associated power supply, and the control panel switches and control relay used in the aircraft. The 8000 psi (55 MPa) hydraulic pump, incorporated in the aircraft for the AFCAS installation, was not included in the lab set-up since the pump performed successfully in the previous Phase V of the AFCAS program and the potential benefits from including it in the lab set-up did not warrant the added expense. An 8000 psi (55 MPa) laboratory hydraulic pump was utilized for all tests requiring high pressure hydraulic flow.

4.3 INTEGRATION TESTS AND RESULTS

4.3.1 Lab Set-Up

A lab wire harness was used configured to simulate the aircraft wiring. A terminal strip/interconnection board provided control, test points, and the interface between the wire harness, system components, and lab test equipment. A pictorial of the lab set-up is shown in Figure 4-1, and the associated block diagram is depicted in Figure 4-2.

A portable hydraulic source with limited flow, .2 gpm @ 10,000 psi (76 L/min @ 69 MPa), was used during initial power application and testing. The 14 gpm @ 8000 psi (53 L/min @ 55 MPa) laboratory hydraulic system was utilized for all final system response and performance tests.

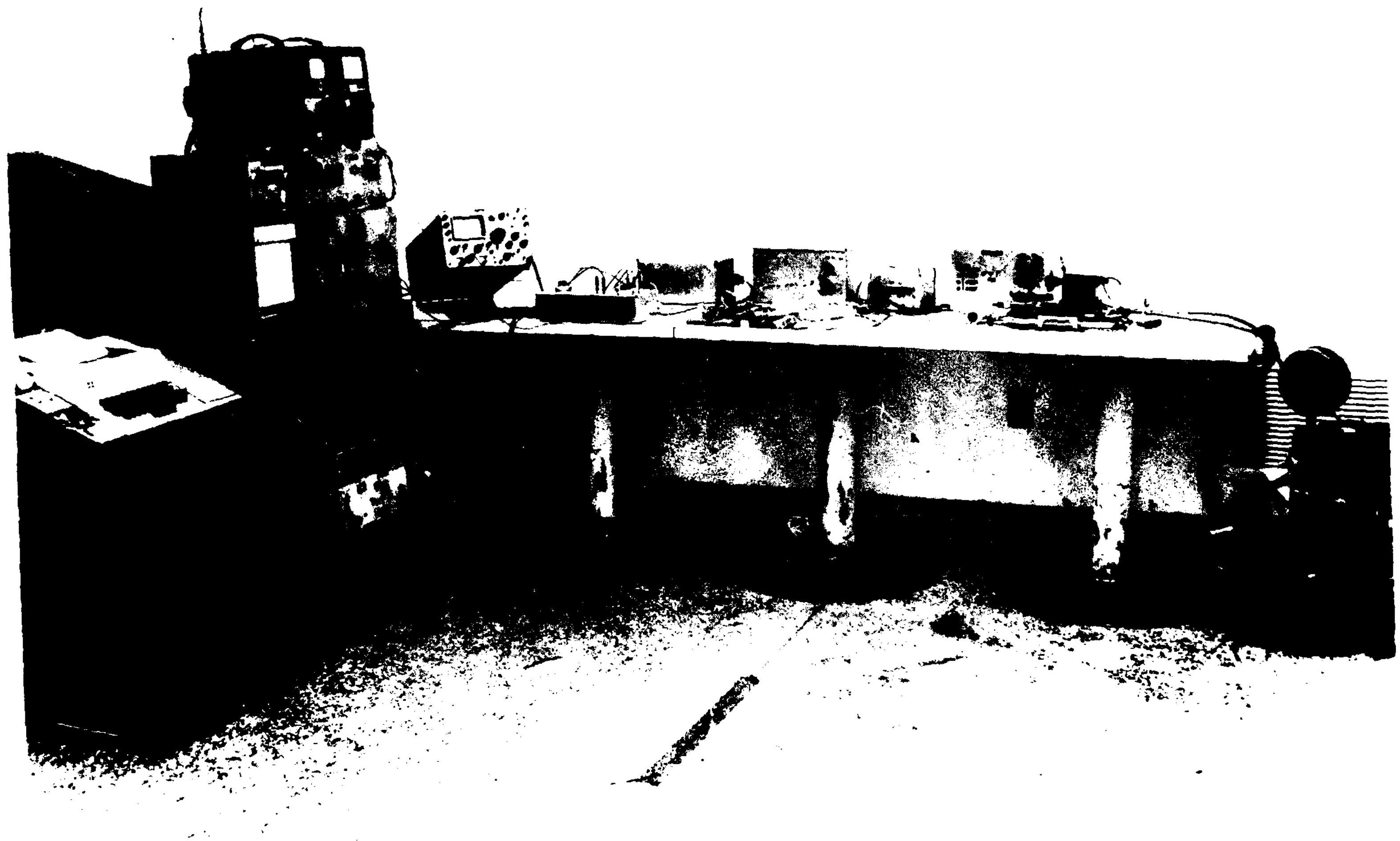


Figure 4-1 Lab Test Setup Pictorial

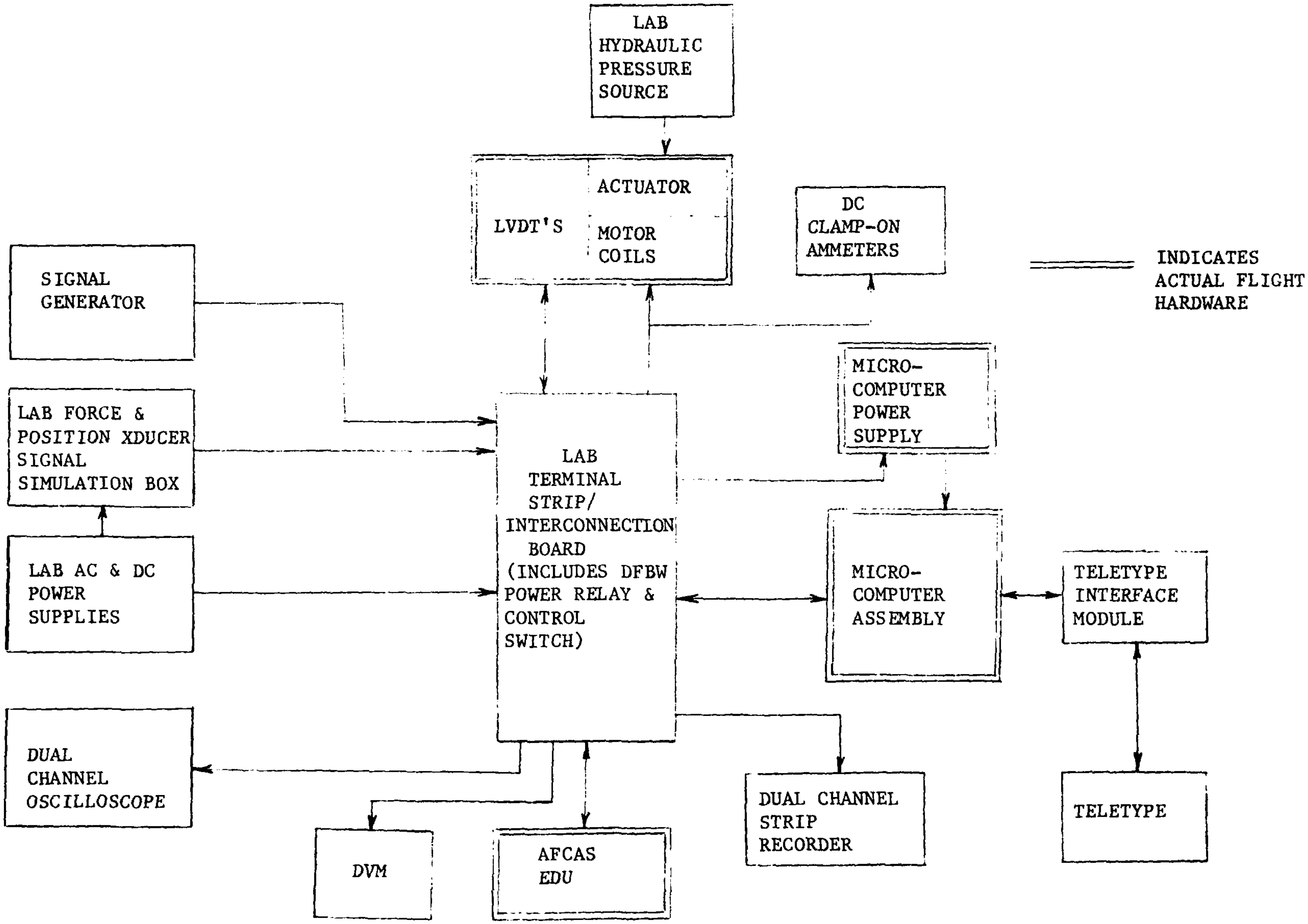


Figure 4-2 Lab Test Setup Block Diagram

4.3.2 Transducer Scale Factor and Linearity

4.3.2.1 Pedal Force Transducers - The pedal force transducers were mounted in a laboratory holding fixture and connected to a ± 15 VDC supply. Output voltages versus force inputs were recorded,and plotted in Figure 4-3. Results show that linearity and scale factors were well within the requirements of the DFBW AFCAS system.

4.3.2.2 Actuator LVDT Feedback Transducer - The actuator LVDT feedback transducers were connected to a ± 15 VDC power supply and the output voltages versus position were recorded,and plotted in Figure 4-4. Results show that linearity and scale factors were well within the requirements of the DFBW AFCAS system.

4.3.3 Continuity and Power Checks

4.3.3.1 Continuity - Continuity checks were performed to verify the microcomputer and microcomputer power supply internal wiring, and the lab interconnecting harness and terminal board assembly.

4.3.3.2 Power - Appropriate pins on each system connector were monitored for proper voltages and grounds, prior to applying power to each of the system components.

4.3.4 Calibration

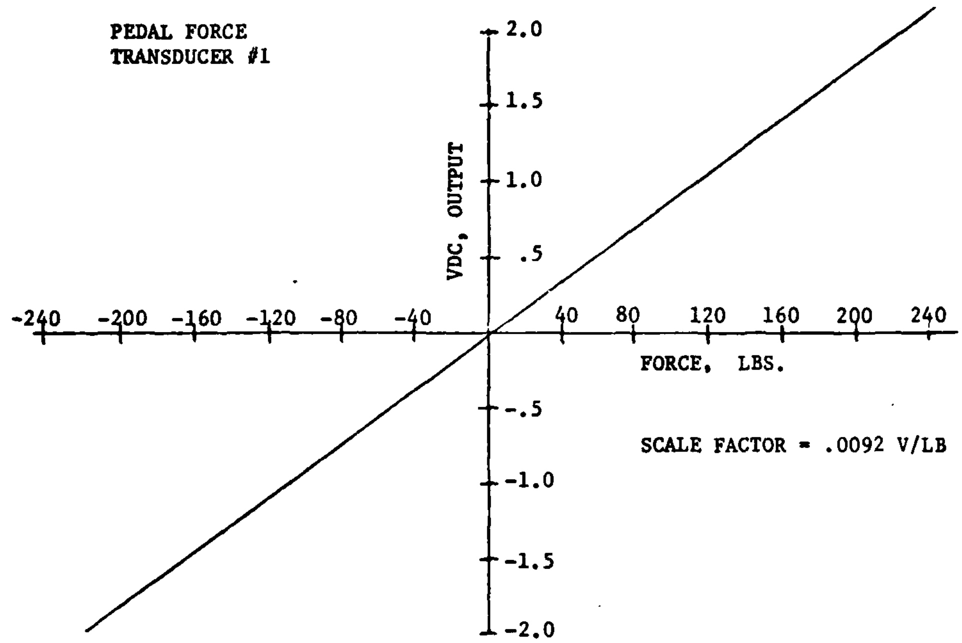
An initial DFBW operational program was developed and loaded into the microcomputer RAM via the teletype and punched paper tape. With hydraulic pressure OFF, static gains of the microcomputer and EDU were measured and adjustments made as necessary to obtain the values shown in Figure 4-5 and Figure 4-6.

4.3.5 Initial Operation

With hydraulic pressure applied, end-to-end operational checks were performed in both the DFBW and the ABU modes. Failure mode sensing and signal amplitude features of the software program were also monitored. Software development was performed on punched paper tape using the teletype interface. After satisfactory software was established the software program was stored in a PROM and installed in the microcomputer for lab testing and verification and subsequent installation in the T-2C aircraft.

4.3.6 Response Characteristics

Overall system response in both the DFBW and ABU modes was determined by applying sinusoidal signals from a function generator to the system force transducer inputs. The rudder actuator was pressurized to



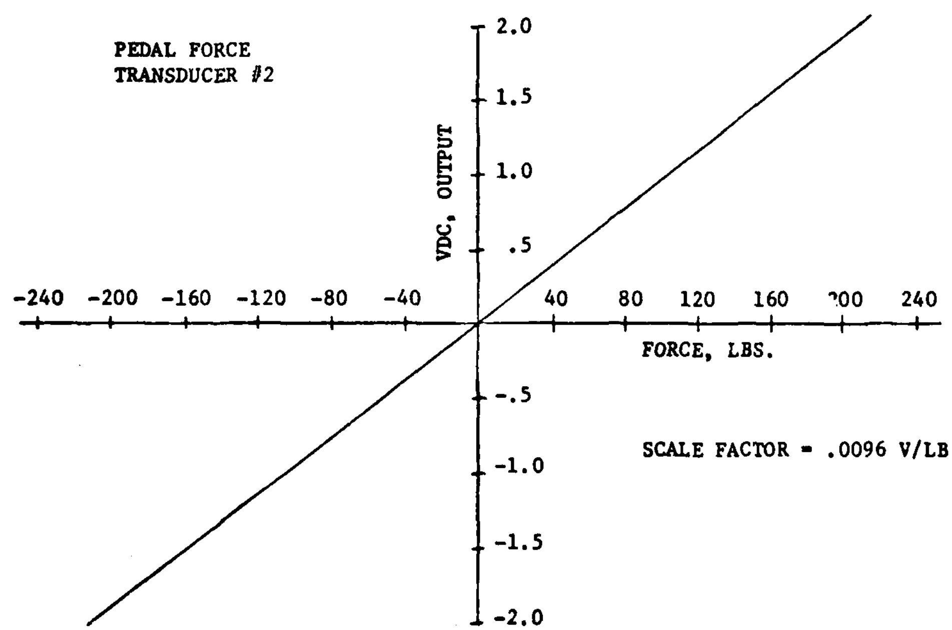
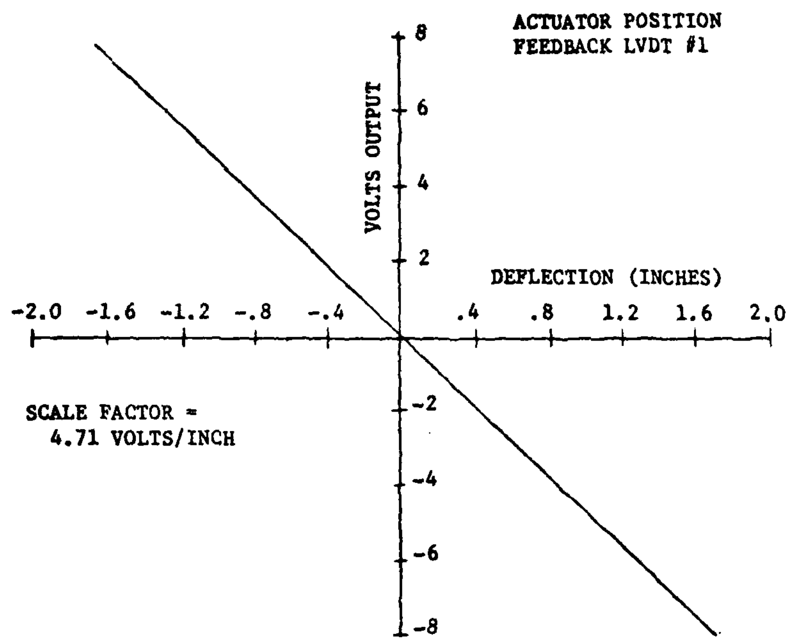


Figure 4-3 Pedal Force Transducers Scale Factor and Linearity



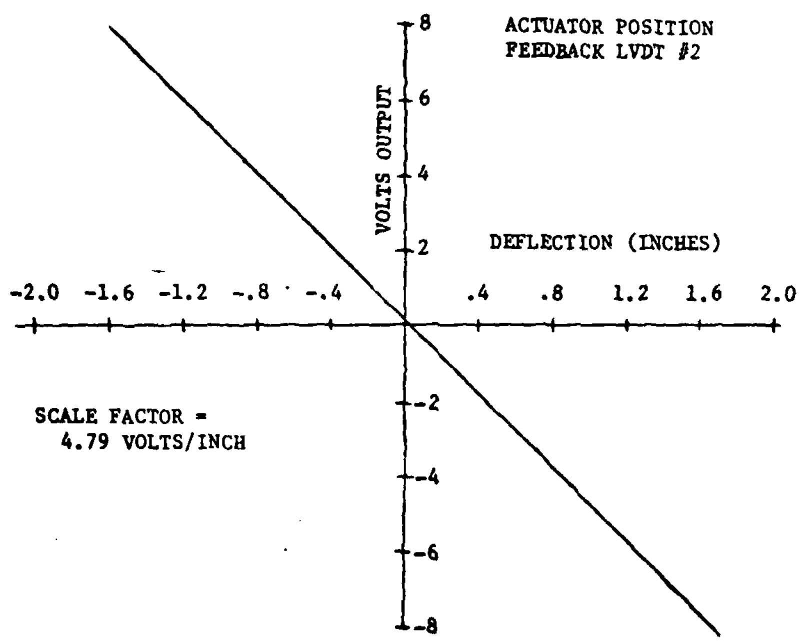


Figure 4-4 Actuator Feedback LVDT's Scale Factor & Linearity

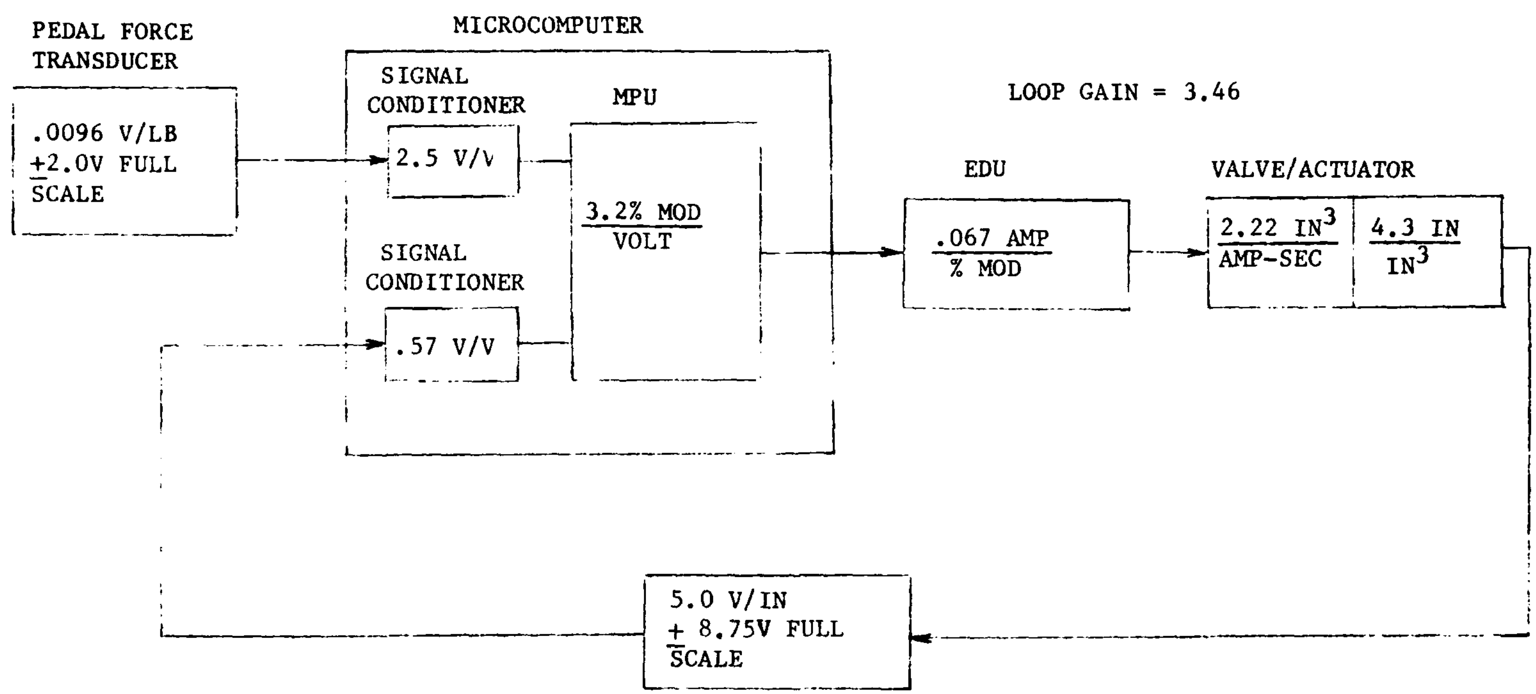


Figure 4-5 System Block Diagram, Digital Fly-By-Wire Mode

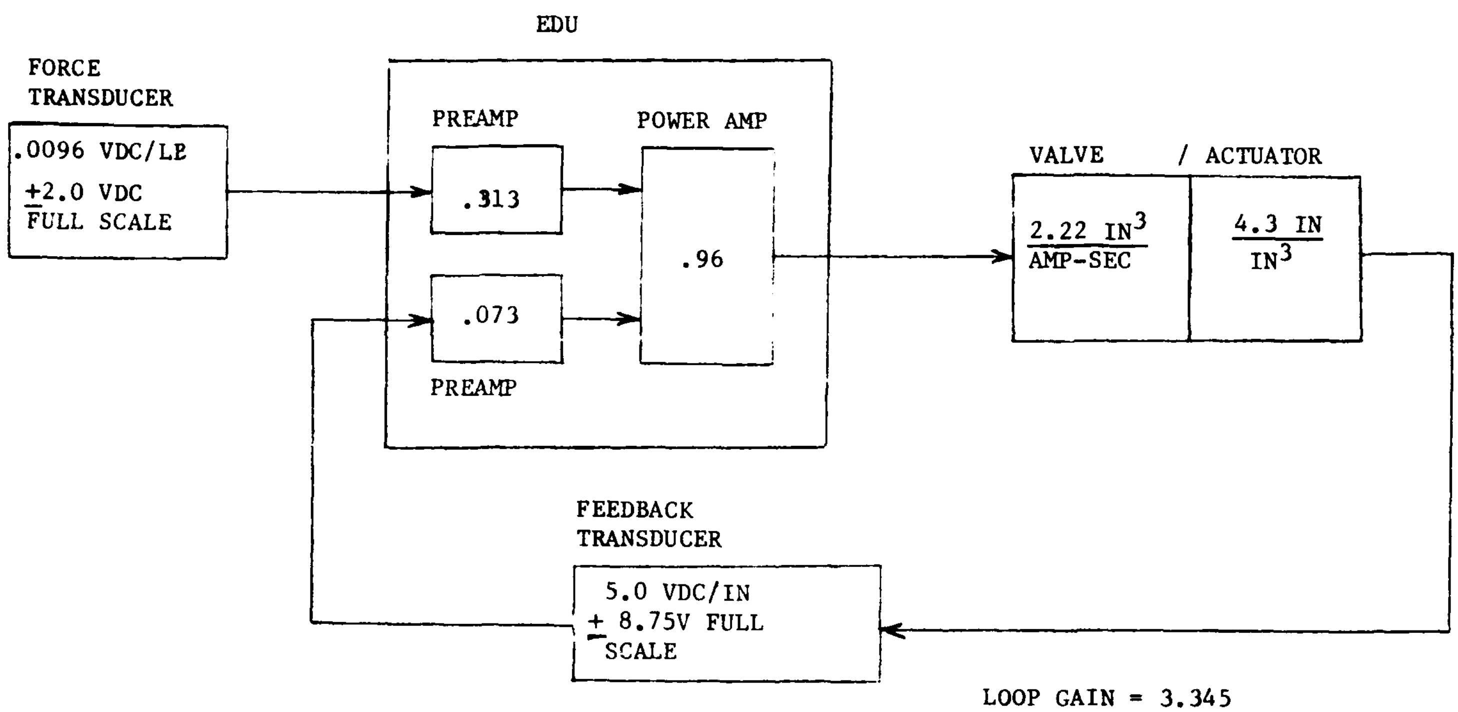


Figure 4-6 System Block Diagram, Analog Back-Up Mode

8000 psi (55 MPa), and the sinusoidal input signal and output piston motion (LVDT feedback) were recorded simultaneously. Response tests were performed with the sinusoidal input signal amplitude set for .2 inch (0.5 cm) piston displacement.

4.3.6.1 ABU Mode System Response - System response capability in the ABU mode is shown in Figure 4-7, with the 3 db point occurring at 10 HZ. Due to T-2C aircraft directional system dynamic requirements, filtering in the EDU reduced system response in this mode as shown in Figure 4-8, with the 3 db point occurring at .75 HZ. This is the same performance capability used in the Phase V flight program.

4.3.6.2 DFBW Mode System Response - System response capability in the DFBW mode is contained in Figure 4-9, with the 3 db point occurring at 6.5 HZ. Because of T-2C aircraft directional system dynamic requirements, filtering in the EDU reduced system response in the DFBW mode as shown in Figure 4-10, with the 3 db point occurring at 1.5 HZ. This response proved entirely satisfactory for the aircraft test installation. Differences in frequency response between the ABU and DFBW modes exist since the EDU was optimized for analog operation. Response tests with the computer providing an analog signal instead of the PWM signal demonstrated that the computer in the loop did not change the analog bandwidth. Company funded tests (Appendix D) have shown that the analog bandpass can be equalled in the pulsed mode of operation if the power amplifier is optimized for pulsed operation.

4.3.7 Microcomputer Bit Resolution

To evaluate the effects of various levels of bit resolution, microcomputer analog programs were assembled for 6, 8, 10, and 12 bit operational modes. The system was driven at 0.5 HZ with an amplitude of approximately ±1 degree of actuator travel. The microcomputer output and actuator feedback signals were simultaneously recorded. Samples of these recordings are contained in Figure 4-11, and demonstrate the granularity of the computer output. While the actuator integrates the computer command to provide apparent smooth travel, the static accuracy will not be better than the resolution of the computer output. The granularity (or delay) in the command will also increase the phase lag in the actuation loop.

For a rudder travel of ±12°, 8 bits gives a resolution of approximately 0.1°, and 10 bits yields approximately 0.025°. For the T-2C rudder application, 8 bit resolution is adequate to perform the control task but does not provide a margin for other factors such as sensor and actuator resolution that might decrease system resolution. The 10 bit resolution utilized for the DFBW AFCAS microcomputer software proved to be completely satisfactory for the subsequent flight test program.

4.3.8 Actuator Motor Coil Current

4.3.8.1 Null Current Versus PWM Frequency - Using the lab simulation test box, a PWM null signal (50% modulation) was artifically generated and connected to the EDU microcomputer input channels.

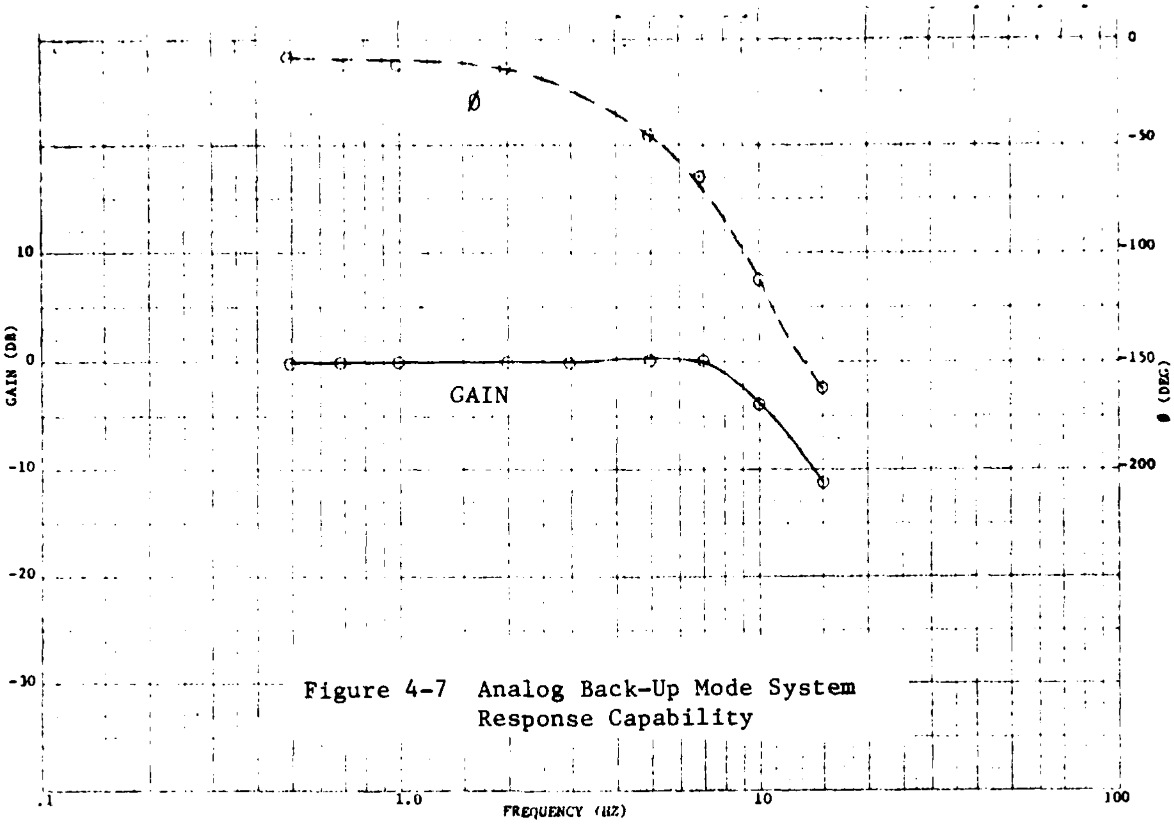


Figure 4-7 Analog Back-Up Mode System Response Capability

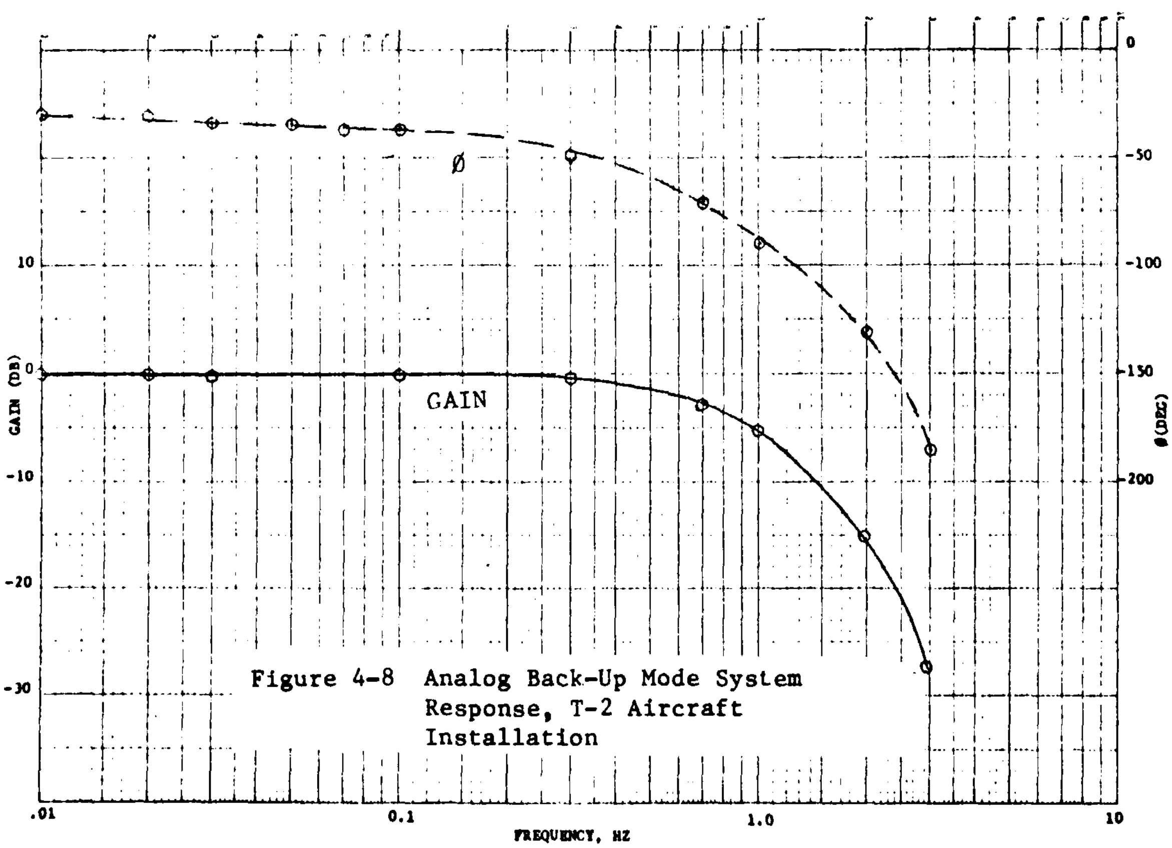


Figure 4-8 Analog Back-Up Mode System Response, T-2 Aircraft Installation

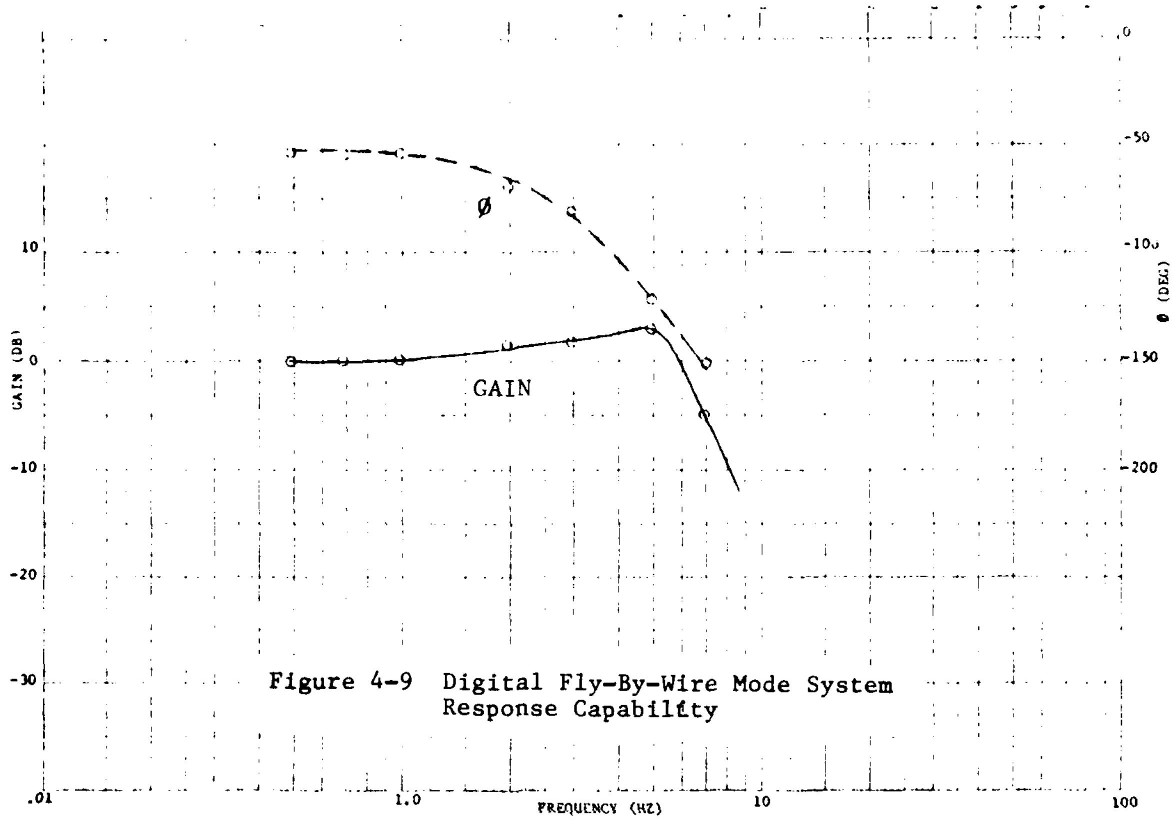


Figure 4-9 Digital Fly-By-Wire Mode System Response Capability

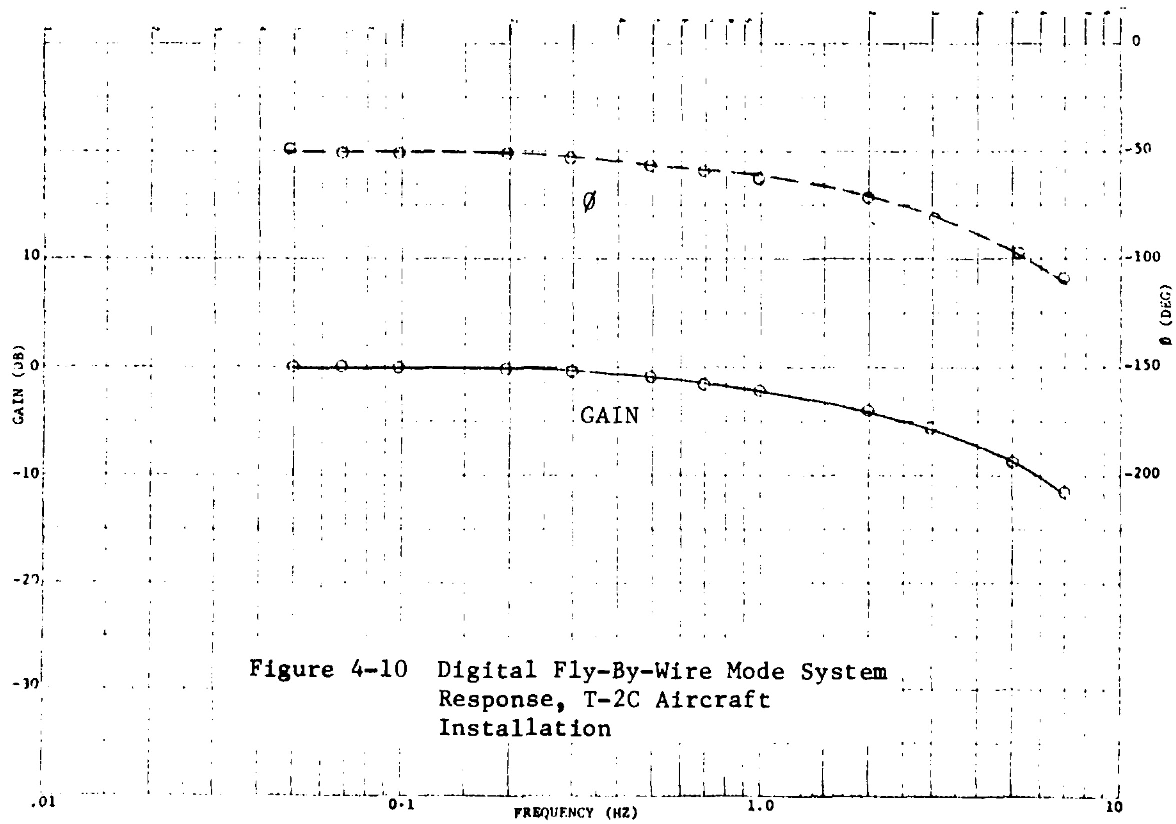


Figure 4-10 Digital Fly-By-Wire Mode System Response, T-2C Aircraft Installation

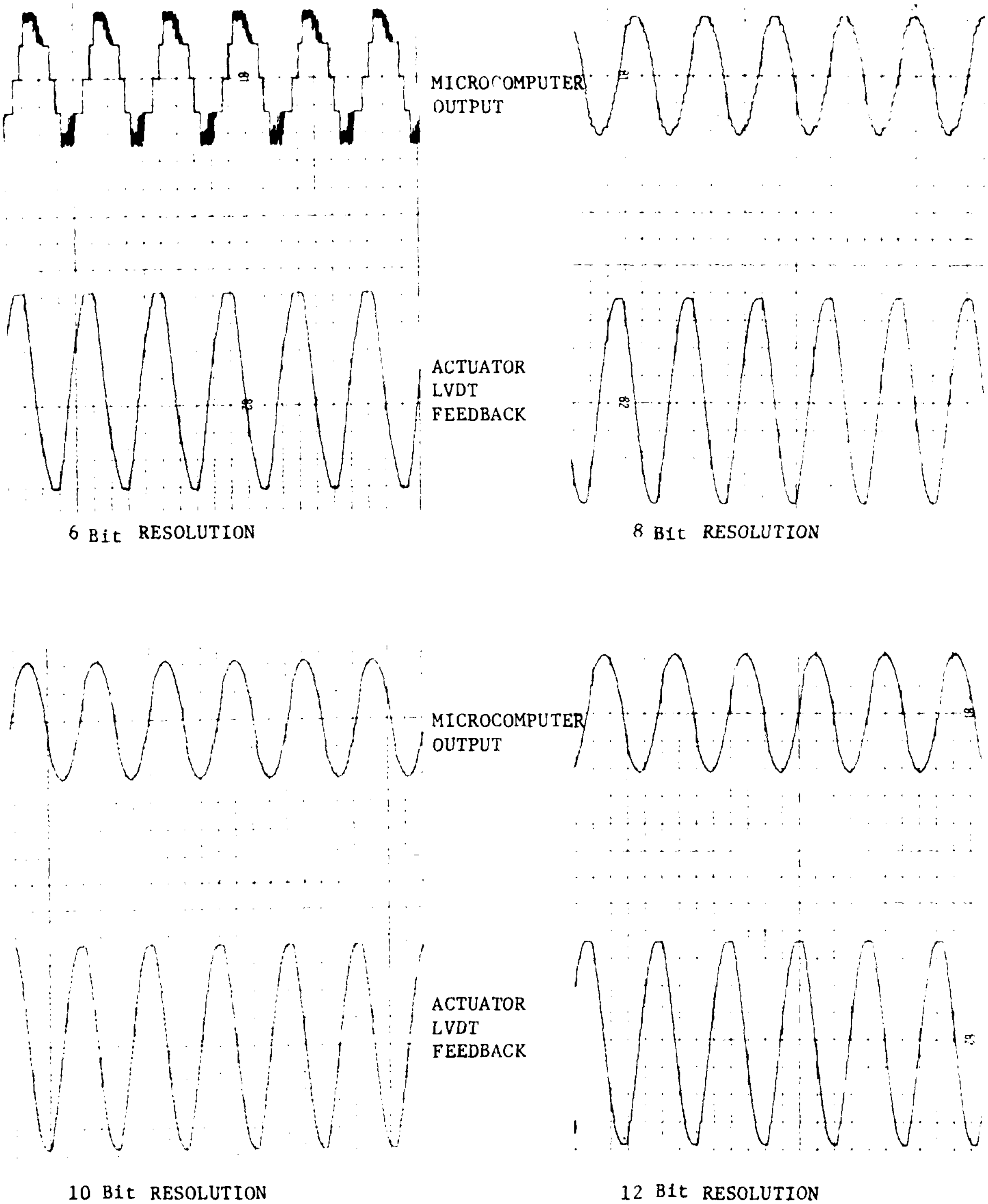


Figure 4-11 Microcomputer Performance Versus Bit Resolution

The PWM null signal repetition rate was varied from 100 to 1000 HZ, and the resulting motor coil current plotted in Figure 4-12. The plot shows that minimum null current is reached at 500 HZ as the PWM repetition rate is increased. This coincides with previous R&D data generated by NAAD-C, and was the PWM repetition rate frequency chosen for the existing microcomputer flight software program.

The 500 HZ signal frequency is also well above the mechanical resonance of the torque motor, which was determined to be 230 HZ. By making the pulse rate well above the natural frequency of the torque motor, no mechanical motion or resonance occur in the motor.

4.3.8.2 Motor Coil Current Waveforms - Using the lab simulation test box, microcomputer output PWM null (50% modulation) and maximum (88% modulation) drive signal,at PWM repetition rates of 100, 500, and 1000 HZ,were simulated and connected to the EDU microcomputer inputs. The simulated drive signals and the resultant motor coil current waveforms were photographed with an oscilloscope camera.

The 500 HZ data contained in Figure 4-13 shows the coil current is nearly DC, due to the inductance of the motor coils. At 100 HZ, Figure 4-14, larger coil current variations occur due to the reduced repetition rate frequency. The 1000 HZ data contained in Figure 4-14 is nearly identical to the 500 HZ data and shows no beneficial reduction in coil current ripple at the higher frequency.

4.3.9 Microcomputer Power Supply Characteristics

The ±12 VDC and the +5 VDC microcomputer power supply outputs were monitored during system operation with a DVM and oscilloscope to measure and record effects of system loading on power supply voltage and ripple. The following readings were obtained:

Parameter, VDC	Measured, VDC	Ripple
12 VDC	12.2 VDC	25 MV, pk. to pk.
-12 VDC	-12.2 VDC	25 MV, pk. to pk.
5 VDC	5.14 VDC	10 MV, pk. to pk.

No changes in the above readings were observed while cycling the system throughout its operating range.

4.4 ENVIRONMENTAL TESTS

Temperature and altitude tests were performed on the AFCAS microcomputer and associated power supply. A Tenney environmental chamber, located in the NAAD-C Thermo Lab, was utilized. Components located in the chamber included the microcomputer, power supply, AFCAS amplifier, and the lab harness and terminal board. The aircraft actuator was located outside the chamber and was used as the electrical load. Hydraulic power was not utilized.

The tests consisted of a 2-hour 32°F (0°C) "cold soak" @ 30,000 ft. (9.14 km) altitude, followed by a 2-hour soak at 122°F (50°C) and sea level pressure. Command signals were applied to the LVDT and F/T inputs via the lab test simulator box and the microcomputer output PWM modulation and actuator coil current were recorded at 15 minute intervals.

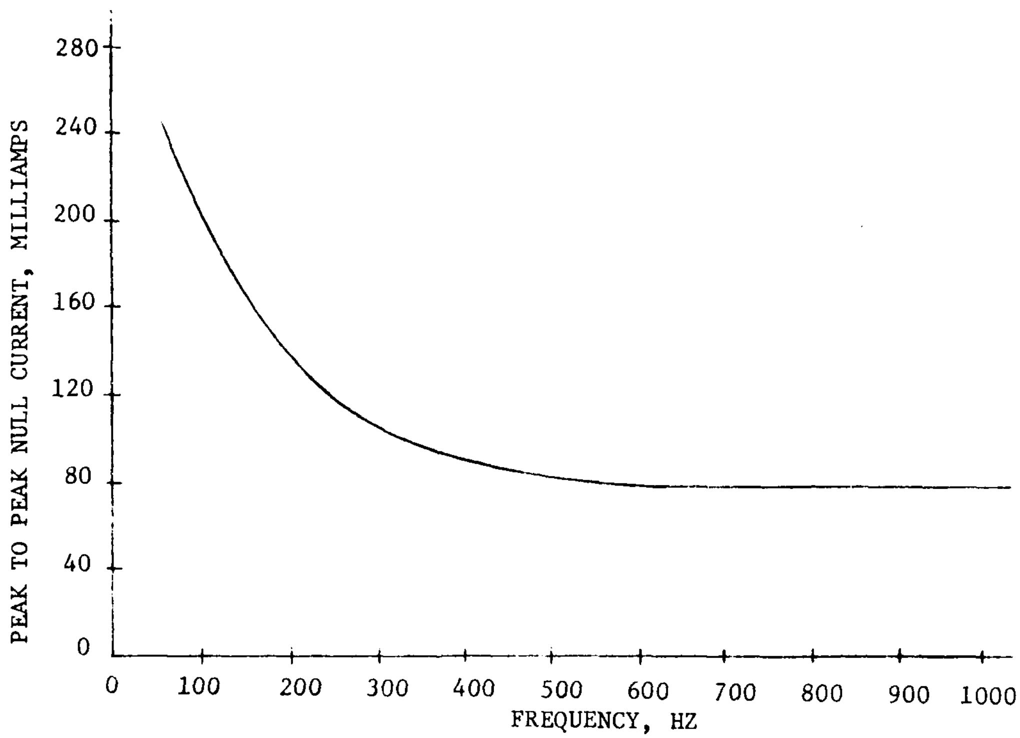
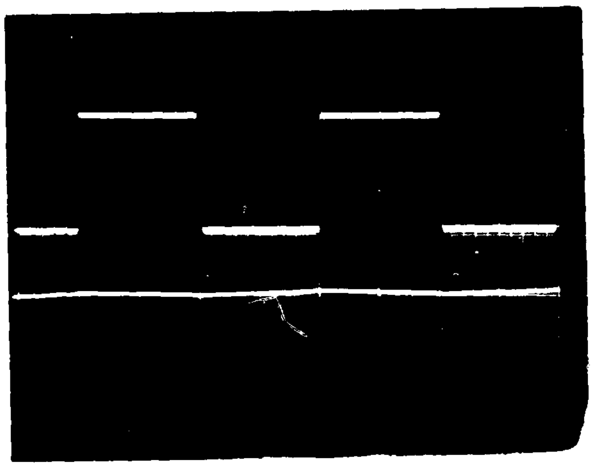


Figure 4-12 Motor Coil Current Versus PWM Null Signal Frequency

.5 MILLISEC/CM

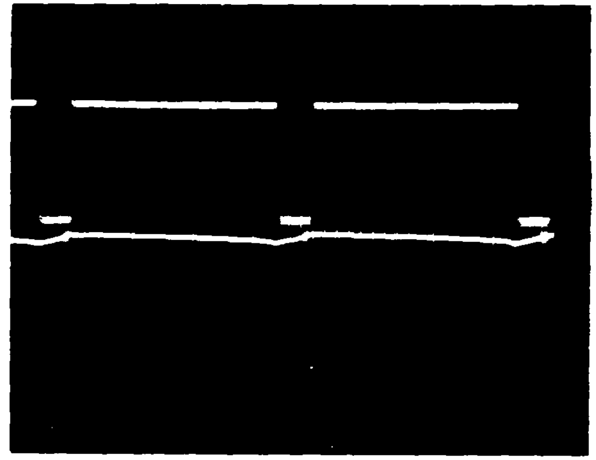


500 HZ NULL SIGNAL (50% MODULATION)

PWM SIGNAL
10 V/CM

COIL
CURRENT
2.5 AMPS/
CM

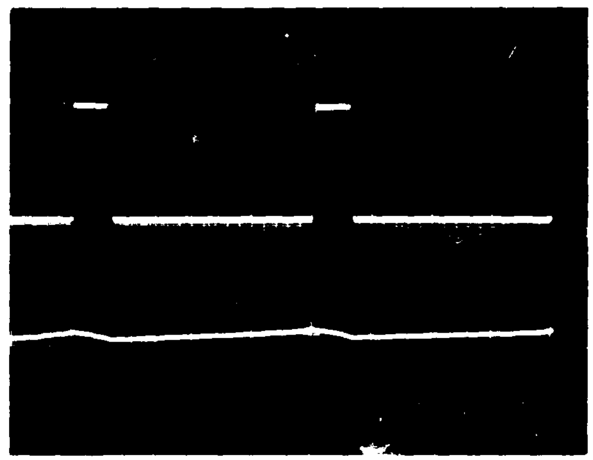
.5 MILLISEC/CM



500 HZ DRIVE POSITIVE (88% MODULATION)

1 CM

.5 MILLISEC/CM



500 ' DRIVE NEGATIVE (12% MODULATION)

Figure 4-13 Motor Coil Current Waveforms, PWM Frequency = 500 HZ

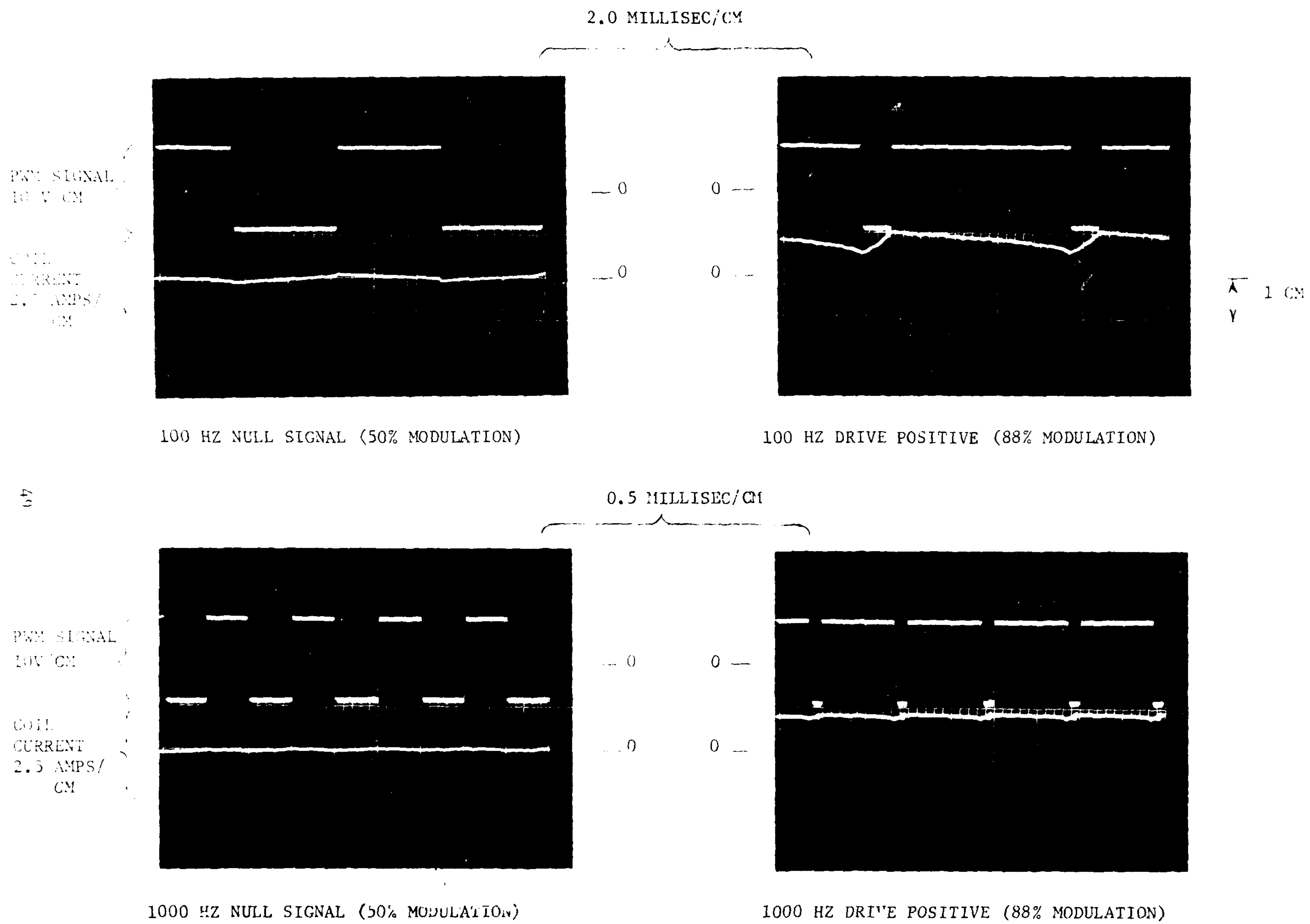


Figure 4-14 Motor Coil Current Waveforms, PWM Frequency = 100 HZ & 1000 Hz

Two air temperature thermocouples were located in the microcomputer. One air temperature and one transformer chassis thermocouple were located in the microcomputer power supply. These temperatures were also recorded at 15 minute intervals.

No failures or abnormal system operations were noted during the tests. The highest temperatures recorded were the power supply air temperature and transformer chassis, which both read 140°F (60°C) after 2 hours at SL pressure and 122°F (50°C) chamber ambient temperature.

Figure 4-15 contains the environmental test temperature/time/altitude cycle and corresponding equipment temperature readings.

Table II contains microcomputer pulse width modulation outputs and total actuator coil current readings versus command inputs, recorded prior to the temperature/pressure cycle, at atmospheric pressure and 73°F (23°C) ambient. Corresponding data taken at 15 minute intervals for the remainder of the test showed no change in modulation outputs and .010 amperes maximum variation in coil current readings compared to the Table II readings.

TABLE II
MICROCOMPUTER PULSE WIDTH MODULATION OUTPUT & ACTUATOR COIL CURRENT, MICROCOMPUTER ENVIRONMENTAL TESTS, TIME ZERO @ 73°F (23°C) & ATMOSPHERIC PRESSURE

MICROCOMPUTER LVDT INPUTS, VOLTS	MICROCOMPUTER PEDAL FORCE XDCR. INPUTS, VOLTS	MICROCOMPUTER OUTPUT % MODULATION	ACTUATOR COIL CURRENT, AMPS
0	0	50	0.015
8.75	0	88	2.75
8.75	-2.0	50	0.020
0	-2.0	12	-2.65
0	2.0	88	2.75
-8.75	2.0	50	0.006

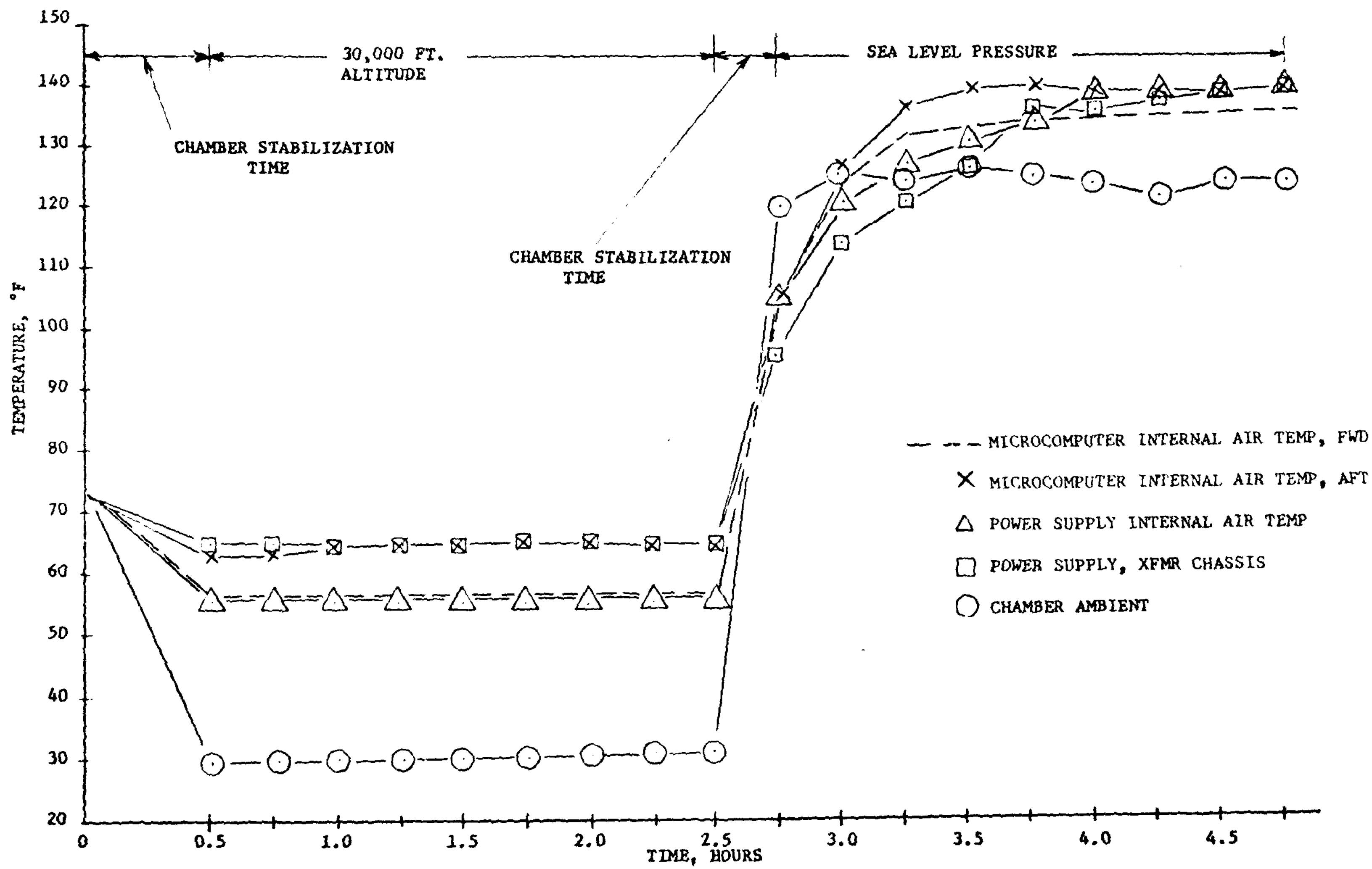


Figure 4-15 Temperature/Time/Altitude Cycle, Microcomputer & Microcomputer Power Supply Environmental Test

5.0 FLIGHT TEST PROGRAM

5.1 AIRCRAFT INSTALLATION

Procedure details for checking the system in the aircraft are given in Appendix C. A summary of steps taken to ensure proper operation of the system is presented in the following paragraphs.

5.1.1 Continuity and Power Checks

Continuity checks were performed on the aircraft wire harness per Drawing #8691-546606A, Wiring Diagram - Advanced Flight Control Actuation System (Figure 5-1). Power was subsequently applied to the aircraft wire harness without the system components connected, and appropriate pins on each connector were monitored for proper voltages and grounds.

5.1.2 Electrical Checks

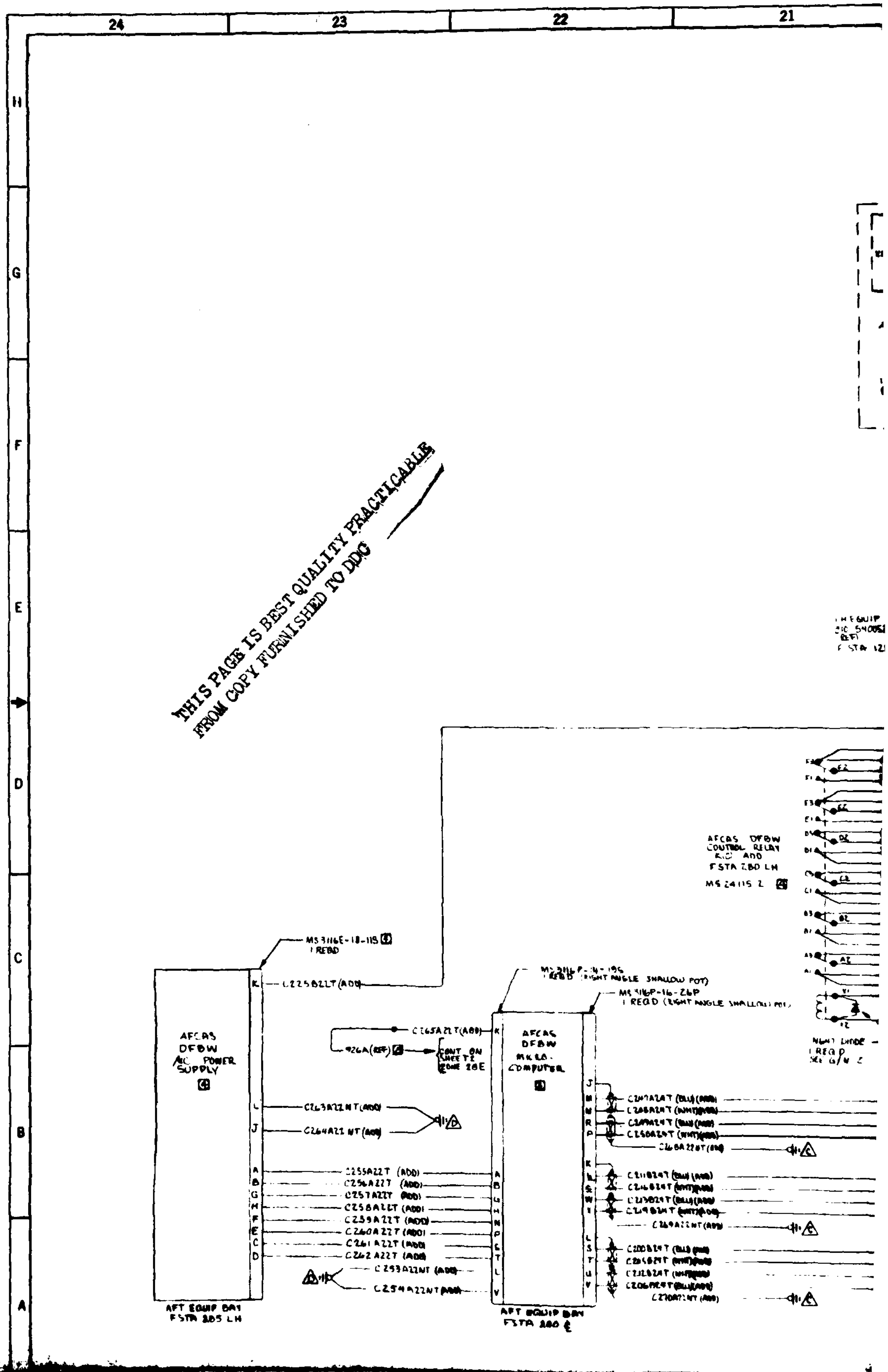
After successful completion of continuity and power checks, the harness was connected to the system components. With electrical power on and the hydraulic pump disabled, the rudder was manually positioned at $0 \pm 1/4°$ and the rudder to actuator linkage adjusted until the position LVDT transducer outputs read $0 \pm .10$ VDC. With no pedal force applied to the rudder pedals, system nulls were measured in both the DFBW and ABU modes and bias pots adjusted as required to achieve the proper nulls. Force was then alternately applied to the rudder pedals in both modes, and the proper indicator lights and voltages verified on the AFCAS test box. No problems were encountered with the foregoing steps.

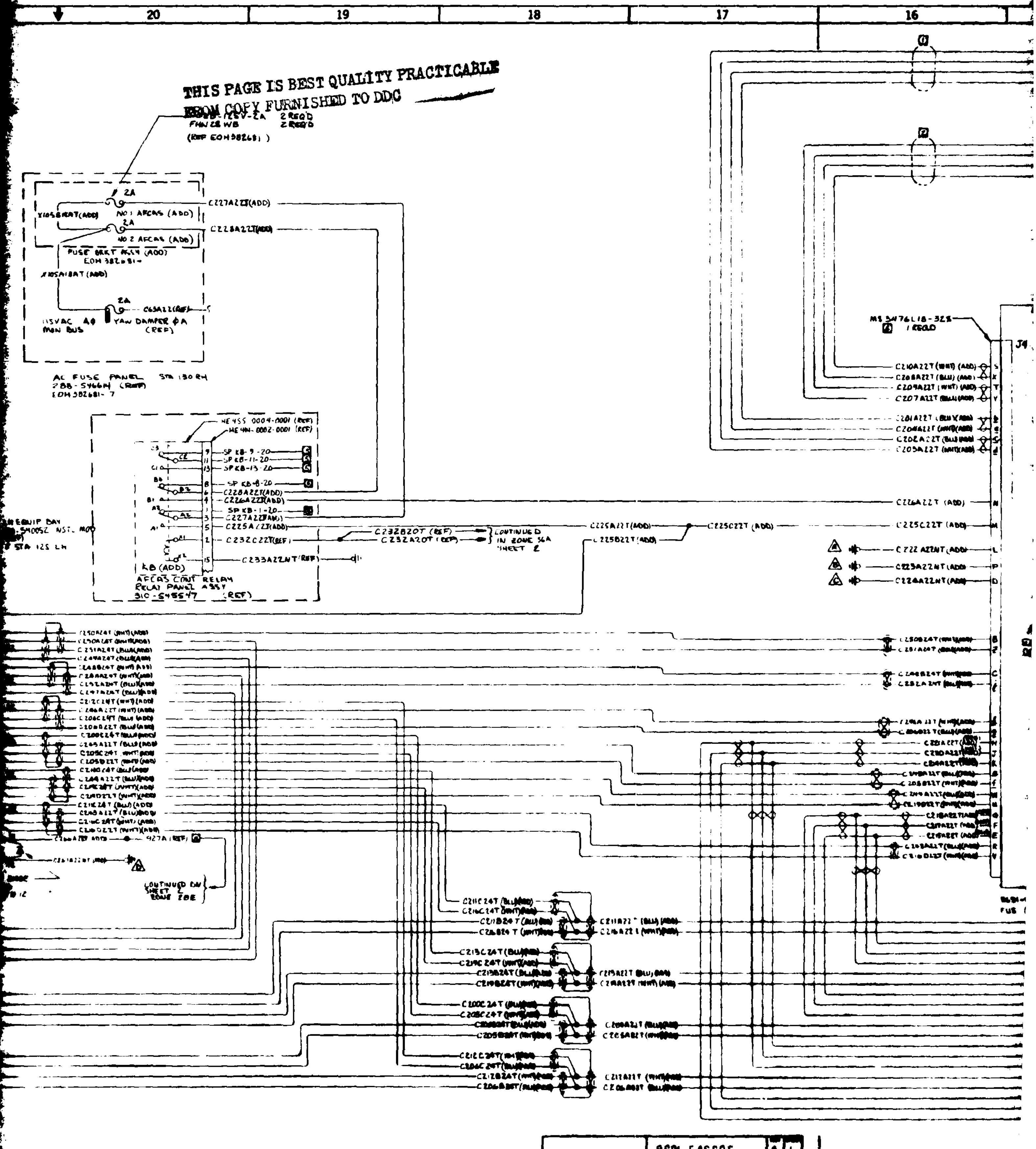
5.1.3 Hydraulic Checks

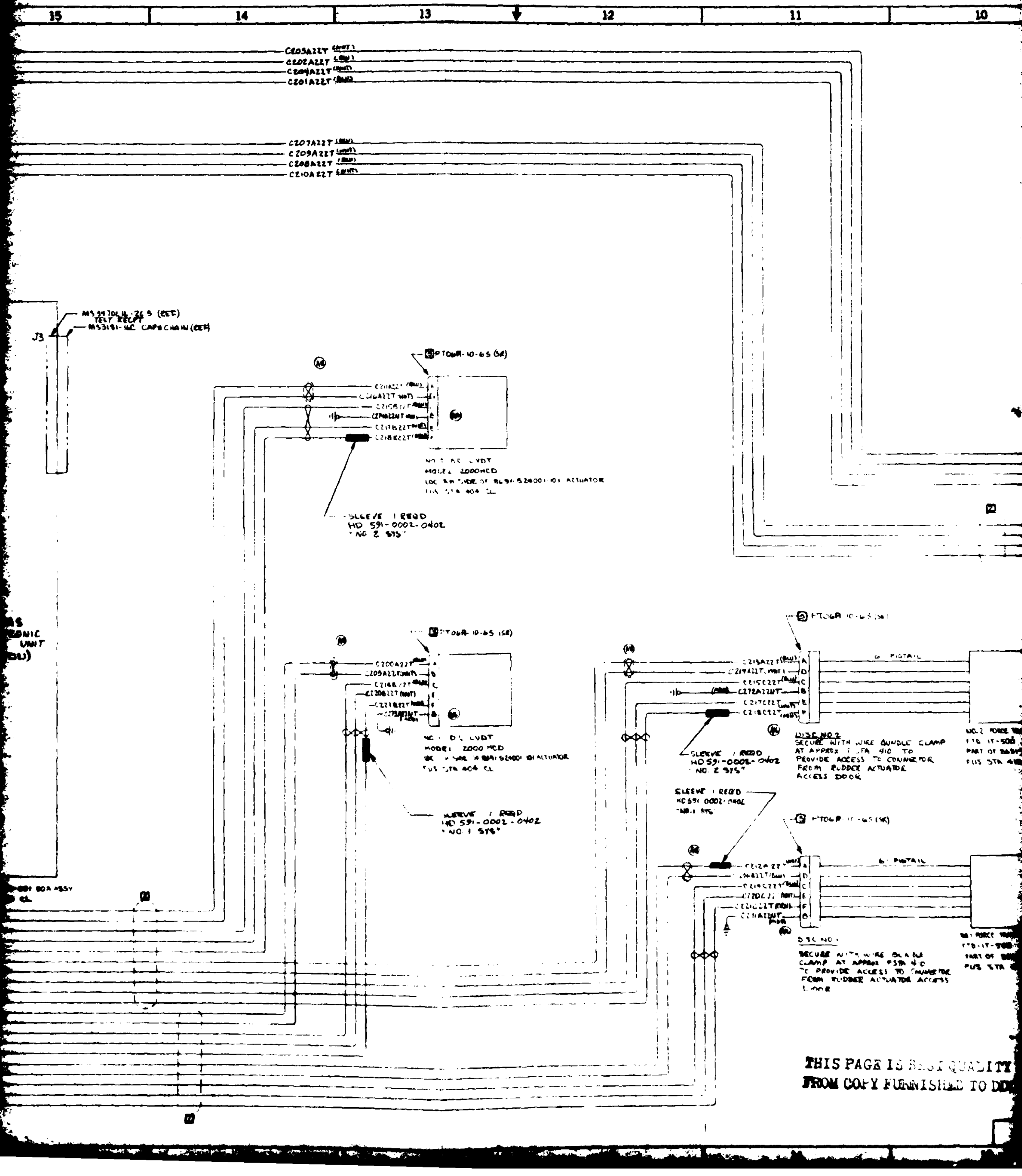
Procedure details are given in Appendix C. The first task involved filling and bleeding the 8000 psi (55 MPa) system. A bleed valve was installed in the return line in the RH speed brake well. A ground cart was connected to the aircraft and the system was filled with MIL-H-83282 fluid. With 25 psig (.2 MPa) applied to the T-2C reservoir, air was bled from a port on the heat exchanger and from the bleed valve in the return line.

A leak check was made on the 8000 psi (55 MPa) portion of the system. Pressures up to 8000 psi (55 MPa) were applied; no external leakage occurred. Pressure was increased sufficiently to operate the test system relief valve (9000 psi/62 MPa). No leakage or malfunctions were observed.

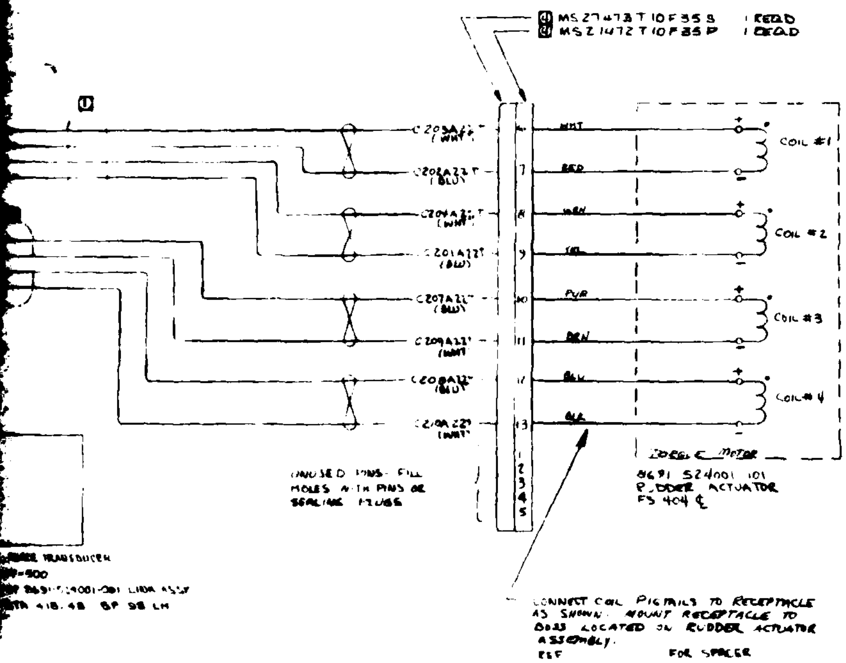
The T-2C 3000 psi (20.7 MPa) system was then pressurized with a service ground cart and the various subsystems were operated. No problems were encountered.


24
23
22
21
H
G
F
E
D
C
B
A
AFCAS DFBW A/C POWER SUPPLY
AFT EQUIP BAY FSTA 285 LH
AFCAS DFBW MKLD. COMPUTER
AFT EQUIP BAY FSTA 280 ℄
AFCAS DFBW CONTROL RELAY
FSTA 280 LH
CONT ON SHEET 2 ZONE 28E


20
19
18
17
16
AC FUSE PANEL STA 130 RH
AFCAS CONT RELAY
RELAY PANEL ASSY
CONTINUED IN ZONE 34A SHEET 2
CONTINUED ON SHEET 2 ZONE 20E
MS 3476L18-32S
J4



15
14
13
12
11
10
C205A22T
C202A22T
C204A22T
C201A22T
C207A22T
C209A22T
C208A22T
C210A22T
J3
SLEEVE 1 REQD
HD 591-0002-0402
"NO 2 SYS"
SLEEVE 1 REQD
HD 591-0002-0402
"NO 1 SYS"
DISC NO 2
SECURE WITH WIRE BUNDLE CLAMP
PROVIDE ACCESS TO CONNECTOR
FROM RUDDER ACTUATOR
ACCESS DOOR



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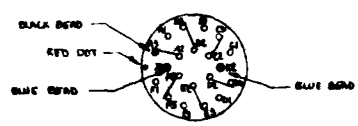
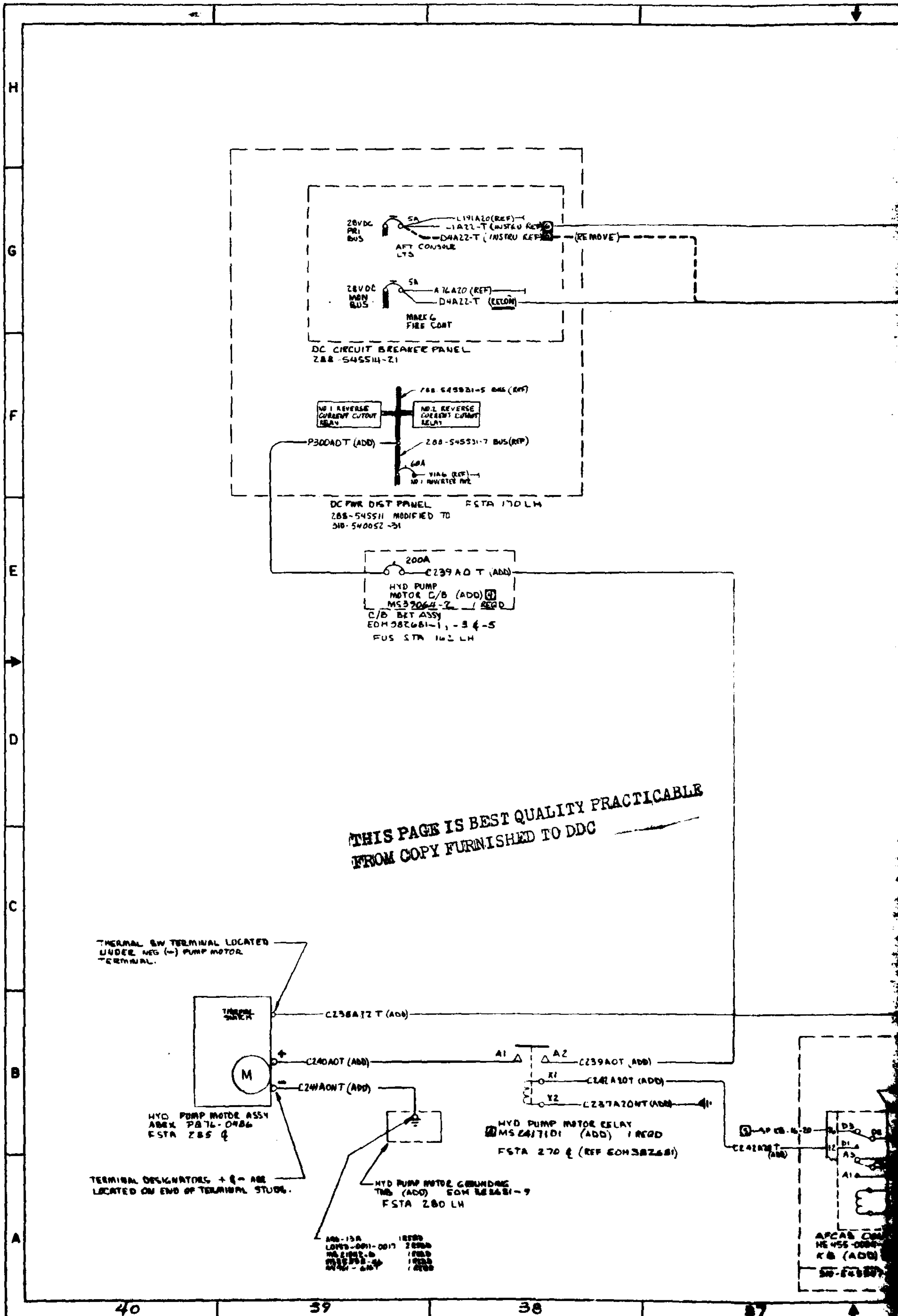


HEADER DIAGRAM FOR MS24185-2 RELAY (VIEWED FROM BOTTOM)

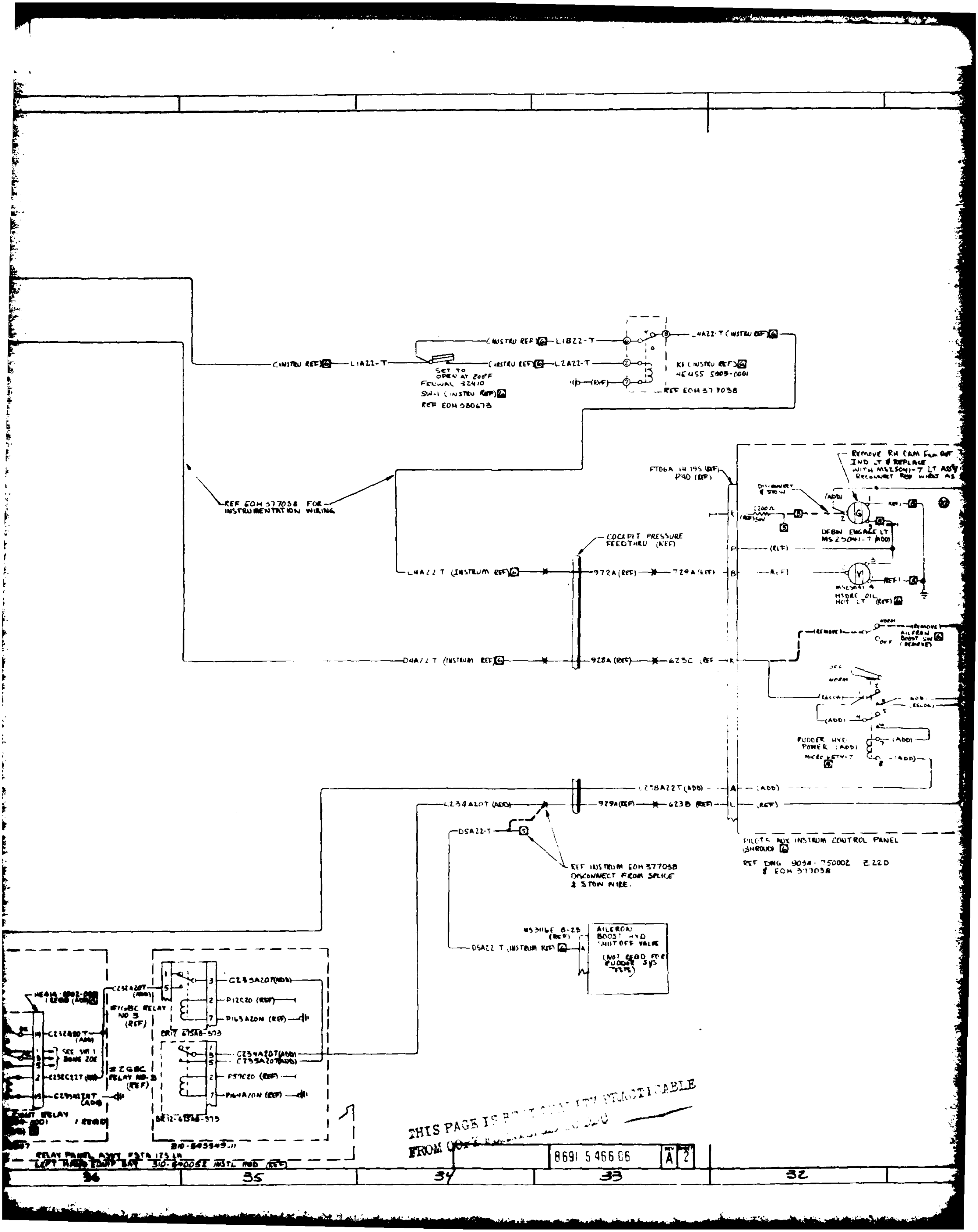
13 RICAD SPEC HA0113-013 FORMS A PART OF THIS
12 CONNECT IN647 DIODE BETWEEN TERMINALS X1 & X2 OF ... POT RELAY IN ACCORDANCE WITH ST0113HA0017 USING ... ST0108HA0009. COVER IN647 DIODE IN POTTING TO ... TO VIBRATION.
11. SYMBOL △ INDICATES GROUND STUDS TO BE IDENTIFIED A, B & C TO PROVIDE HOOKUP CONTROL FOR SYSTEM & SHIELD GROUND WIRES.
10. INSTRUMENTATION WIRING. REF DWG 3034-TC0002.
9. TO BE USED ON T-2C SHIP 1, BUNO152382 FOR TEST PER E.O. 8691.
8. INSTRUMENTATION WIRING. REF 4804517038.
7. SYMBOL DENOTES MS25274 WIRE END CAP TO BE USED ON SPARE WIRE.
6. MATING CONNECTOR SUPPLIED WITH EQUIPMENT ITEM.
5. SYMBOL DENOTES SYS NO. 2 WIRES. BUNDLE & ROUTE SEPARATE FROM SYS NO. 1 WIRES.
4. SYMBOL DENOTES SYS NO. 1 WIRES. BUNDLE & ROUTE SEPARATE FROM SYS NO. 2 WIRES.
3. REF THE FOLLOWING DWGS & ED'S FOR LOCATION OF COMPONENTS
8691-546603 ELECTRICAL INSTALLATION
8691-580010 HYDRAULIC INSTATION
8691-524001 RUDDER INSTALLATION
EOH 582481
2. PART FURNISHED BY CAD ENGINEERING DEPT 71-5...
1. SEE DWG. 288-940002 FOR FABRICATION & SPECIFICA...
NOTES UNLESS OTHERWISE NOTED

TY PRACTICABLE
DDC

8691-546806 A 1



H
G
F
E
D
C
B
A
40
39
38
37
28VDC PRI BUS
5A
L191A20(REF)
D4A22-T (INSTRU REF)
(REMOVE)
AFT CONSOLE LTS
28VDC MON BUS
5A
A76A20 (REF)
D4A22-T
MARK 6 FIRE CONT
DC CIRCUIT BREAKER PANEL
288-545514-21
NO 1 REVERSE CURRENT CUTOUT RELAY
NO 2 REVERSE CURRENT CUTOUT RELAY
288-545531-7 BUS(REF)
P300A0T (ADD)
60A
DC PWR DIST PANEL
FSTA 170 LH
288-545511 MODIFIED TO
310-540052-31
200A
C239A0T (ADD)
HYD PUMP MOTOR C/B (ADD)
MS3506-2 1 REQD
C/B BKT ASSY
EDH582681-1, -3 & -5
FUS STA 162 LH
THERMAL SW TERMINAL LOCATED UNDER NEG (−) PUMP MOTOR TERMINAL.
THERMAL SWITCH
C238A12T (ADD)
M
C240A0T (ADD)
C241A0NT (ADD)
A1
A2
C239A0T (ADD)
X1
X2
C242A20T (ADD)
C237A20NT (ADD)
HYD PUMP MOTOR ASSY
ABEX PB76-0486
FSTA 285 ℄
HYD PUMP MOTOR RELAY
MS24171D1 (ADD) 1 REQD
FSTA 270 ℄ (REF EDH582681)
TERMINAL DESIGNATORS + & − ARE LOCATED ON END OF TERMINAL STUDS.
HYD PUMP MOTOR GROUNDING TAB (ADD) EDH582681-9
FSTA 280 LH
D3
D1
A3
A1
AFCAS
K8 (ADD)



(INSTRU REF) L1A22-T
(INSTRU REF) L1B22-T
(INSTRU REF) L2A22-T
L4A22-T (INSTRU REF)
SET TO OPEN AT 200°F
FENWAL 32410
SW-1 (INSTRU REF)
REF EOH 380673
K1 (INSTRU REF)
REF EOH 377038
REF EOH 377038 FOR INSTRUMENTATION WIRING
COCKPIT PRESSURE FEEDTHRU (REF)
L4A22-T (INSTRUM REF)
972A (REF)
729A (REF)
D4A22-T (INSTRUM REF)
928A (REF)
623C (REF)
P40 (REF)
REMOVE RH CAM FAN OFF IND LT & REPLACE WITH MS25041-7 LT ASSY
DISCONNECT & STOW
DFBW ENGAGE LT MS25041-7 (ADD)
HYDRO OIL HOT LT (REF)
AILERON BOOST SW (REMOVE)
OFF
NORM
(RELOC)
(ADD)
RUDDER HYD POWER (ADD)
C238A22T (ADD)
L234A20T (ADD)
929A (REF)
623B (REF)
D5A22-T
REF INSTRUM EOH 377038 DISCONNECT FROM SPLICE & STOW WIRE.
PILOTS AUX INSTRUM CONTROL PANEL (SHROUD)
REF DWG 9034-750002 Z22D & EOH 377038
D5A22-T (INSTRUM REF)
AILERON BOOST HYD SHUT OFF VALVE
(NOT REQD FOR RUDDER SYS TESTS)
C235A20T (ADD)
P12C20 (REF)
P16A20N (REF)
BR12-6758-373
RELAY NO 3 (REF)
C234A20T (ADD)
C235A20T (ADD)
P57C20 (REF)
P64A20N (REF)
RELAY NO 2 (REF)
SEE SHT 1 ZONE 20E
RELAY PANEL ASSY STA 173 LH
LEFT HAND EQUIP BAY 310-840052 INSTL MOD (REF)
8691 5466 06
A
2
36
35
34
33
32

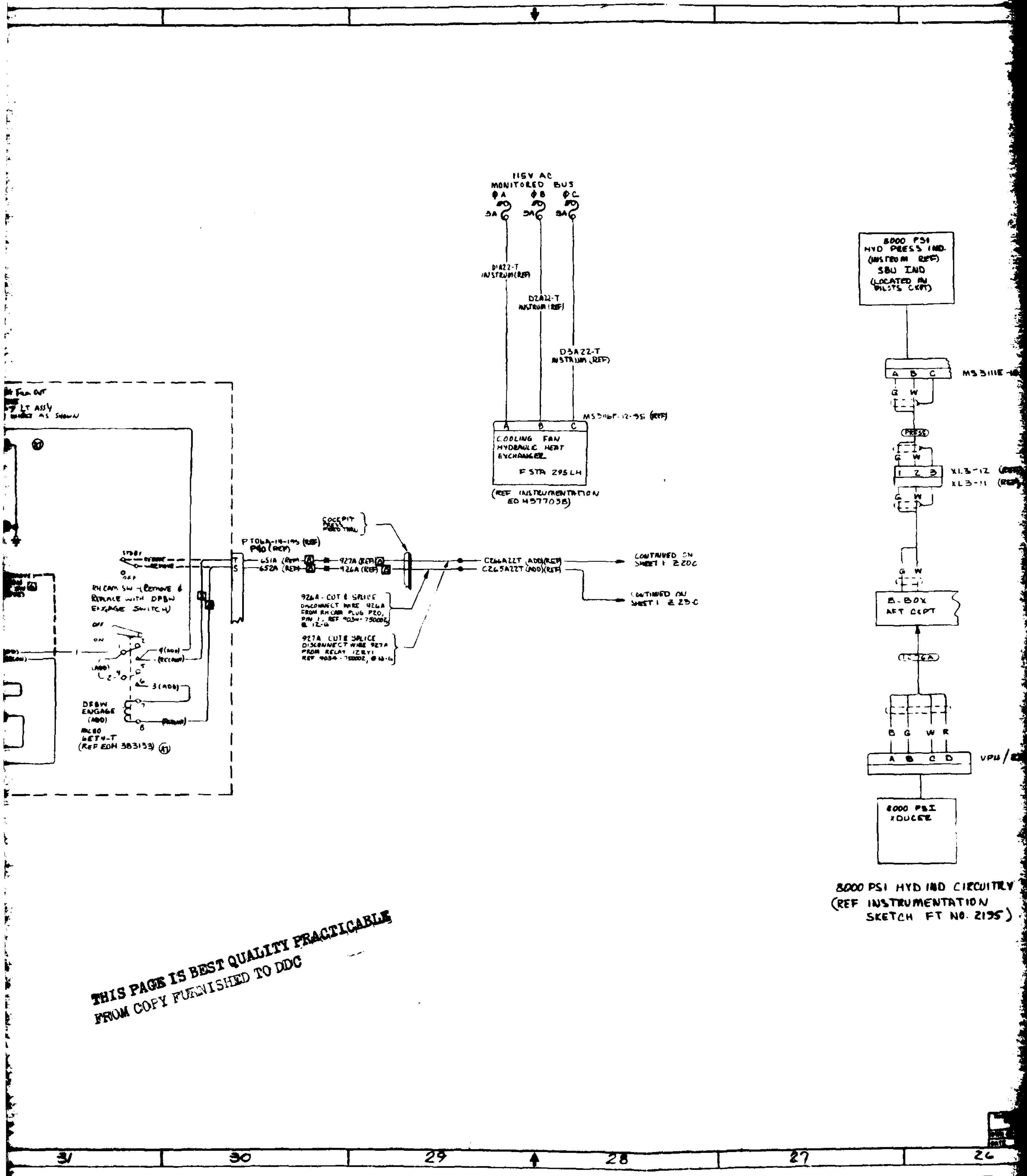
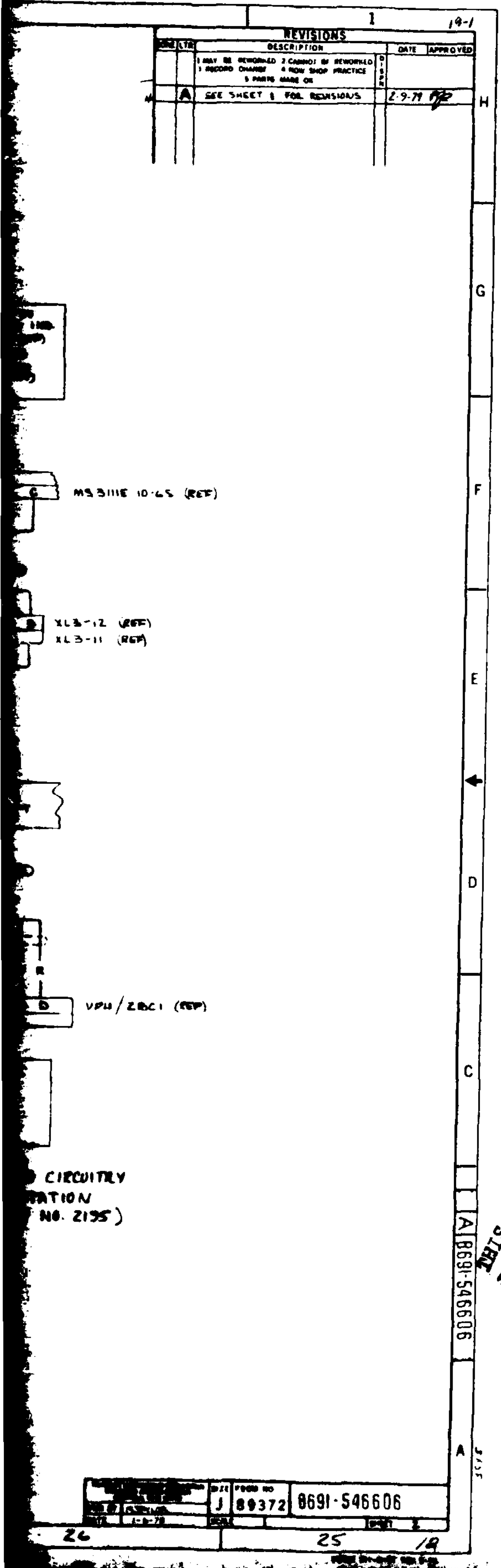

115V AC
MONITORED BUS
ΦA ΦB ΦC
5A 5A 5A
D1A22-T INSTRUM (REF)
D2A22-T INSTRUM (REF)
D3A22-T INSTRUM (REF)
MS3116F-12-3S (REF)
COOLING FAN
HYDRAULIC HEAT EXCHANGER
F STA 295 LH
(REF INSTRUMENTATION ED 4577035)
8000 PSI HYD PRESS IND. (INSTRUM REF) SBU IND (LOCATED IN PILOTS CKPT)
XL3-12 (REF)
XL3-11 (REF)
B-BOX AFT CKPT
B G W R
A B C D
8000 PSI XDUCER
8000 PSI HYD IND CIRCUITRY (REF INSTRUMENTATION SKETCH FT NO. 2155)
COCKPIT PRESS FEED THRU
651A (REF)
652A (REF)
927A (REF)
926A (REF)
C266A22T (ADD)(REF)
C265A22T (ADD)(REF)
CONTINUED ON SHEET 1 Z 22C
CONTINUED ON SHEET 1 Z 23C
926A - CUT & SPLICE DISCONNECT WIRE 926A FROM RH CAM PLUG P20, PIN 1, REF 9034-75000Z, Z 12-G
927A CUT & SPLICE DISCONNECT WIRE 927A FROM RELAY 1Z8Y1 REF 9034-75000Z, Z 12-G
RH CAM SW - (REMOVE & REPLACE WITH DPBW ENGAGE SWITCH)
OFF
ON
3 (ADD)
DPBW ENGAGE (ADD)
MC80 6ET4-T (REF EDH 383133)
STBY
OFF

FIG. 5



8691-546606 SH 2

H

G

F

E

D

C

B

A

RECONNECT WIRE LIST

WIRE NUMBER	TERMINAL	TERMINAL
L5A22 T	—	MS25274-2
D4A22-T	—	M7928/1-13

ADD WIRE LIST

WIRE NO.	TYPE	TERMINAL	TERMINAL
X105B1BAT	M22759/6-18-9	M7928/1-31	M7928/1-31
X105A1BAT	M22759/6-18-9	M7928/1-31	M7928/1-31
P300A0T	MS90284-01-9	[illegible]	[illegible]

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TERMINAL	COLOR
M7928/1-31	—
M7928/1-31	—
[illegible]-0000-0008	—

WIRE NO.	TYPE	TERMINAL	TERMINAL	COLOR
C274A22NT	M22759/16-22-9	—	M7928/1-15	—
C273A22NT	M22759/16-22-9	—	M7928/1-15	—
C272A22NT	M22759/16-22-9	—	M7928/1-15	—
C271A22NT	M22759/16-22-9	—	M7928/1-15	—
C270A22NT	M22759/16-22-9	—	M7928/1-15	—
C269A22NT	M22759/16-22-9	—	M7928/1-15	—
C268A22NT	M22759/16-22-9	—	M7928/1-15	—
C267A22NT	M22759/16-22-9	—	M7928/1-15	—
C266A22T	M22759/16-22-9	—	ST4110206HE0001	—
C265A22T	M22759/16-22-9	—	ST4110206HE0001	—
C264A22NT	M22759/16-22-9	—	M7928/1-15	—
C263A22NT	M22759/16-22-9	—	M7928/1-15	—
C262A22T	M22759/16-22-9	—	—	—
C261A22T	M22759/16-22-9	—	—	—
C260A22T	M22759/16-22-9	—	—	—
C259A22T	M22759/16-22-9	—	—	—
C258A22T	M22759/16-22-9	—	—	—
C257A22T	M22759/16-22-9	—	—	—
C256A22T	M22759/16-22-9	—	—	—
C255A22T	MS22759/16-22-9	—	—	—
C254A22NT	MS22759/16-22-9	—	M7928/1-15	—
C253A22NT	MS22759/16-22-9	—	M7928/1-15	—
C252A24T	M27500-24TG2TN	—	—	BLU
C251A24T	M27500-24TG2TN	—	—	BLU
C250B24T	M27500-24TG2TN	—	—	WHT
C250A24T	M27500-24TG2TN	—	—	WHT
C249A24T	M27500-24TG2TN	—	—	BLU
C248B22T	M27500-24TG2TN	—	—	WHT
C248A22T	M27500-24TG2TN	—	—	WHT
C247A24T	M27500-24TG2TN	—	—	BLU
C246A22T	M7078/26-22-2	—	—	WHT
C245A22T	M7078/26-22-2	—	—	BLU
C244A22T	M7078/26-22-2	—	—	BLU
C243A22T	M7078/26-22-2	—	—	BLU
A9 C242A20T	MS22759/16-20-9	—	M7928/1-23	—
C241A20NT	MS90294-01-9	YAN1001/6 STR-L	YAN1001/6 STR-L	—
C240A07	MS90294-01-9	YAN1001/6 STR-L	YAN1001/6 STR-L	—
C239A07	MS90294-01-9	YAN1001/6 STR-L	HE[illegible]-0008-0008	—
C238A22T	MS22759/16-20-9	—	M7928/1-15	—
C237A20NT	M22759/16-20-9	M7928/1-[illegible]	M7928/1-15	—
C236A20T	M22759/16-20-9	—	—	—
C234A20T	M22759/16-20-9	—	ST4110206HE0001	—
C233A22NT	M22759/16-22-9	M7928/1-15	—	—
C232C22T	M22759/16-22-9	ST4110206[illegible]	—	—
A9 C232B20T	M22759/16-20-9	" [illegible]	—	—
C232A20T	M22759/16-20-9	ST4110206HE0001	—	—

ADD WIRE LIST

WIRE NO.	TYPE	TERMINAL	TERMINAL	COLOR
C228A22T	M22759/16-22-9	M7928/1-15	—	—
C227A22T	M22759/16-22-9	M7928/1-15	—	—
C226A22T	M22759/16-22-9	—	—	—
C225C22T	M22759/16-22-9	ST4[illegible](BF)	—	—
C225B22T	M22759/16-22-9	" (BF)	—	—
C225A22T	M22759/16-22-9	—	ST4110206HE0001	—
C224A22NT	M22759/16-22-9	—	M7928/1-15	—
C223A22NT	M22759/16-22-9	—	M7928/1-15	—
C222A22NT	M22759/16-22-9	—	M7928/1-15	—
C221C22T	M7078/16-22-3	ST410[illegible](BF)	—	ORN
C221B22T	M7078/16-22-3	" (BF)	—	ORN
C221A22T	M7078/16-22-3	ST4110206[illegible]	—	ORN
C220C22T	M7078/16-22-3	ST4[illegible](BF)	—	WHT
C220B22T	M7078/16-22-3	" (BF)	—	WHT
C220A22T	M7078/16-22-3	ST4[illegible]HE0001	—	WHT
C219D22T	M7078/26-22-2	—	—	WHT
C219C24T	M27500-24TG2TN	ST4[illegible]	—	WHT
C219B24T	M27500-24TG2TN	" (BF)	—	WHT
C219A22T	M7078/26-22-2	—	ST4110206HE0001	WHT
C218C22T	M7078/16-22-3	ST4110206HE0001(BF)	—	ORN
C218B22T	M7078/16-22-3	" (BF)	—	ORN
C218A22T	M7078/16-22-3	ST4110206HE0001	—	ORN
C217C22T	M7078/16-22-3	ST4110206[illegible](BF)	—	WHT
C217B22T	M7078/16-22-3	" (BF)	—	WHT
C217A22T	M7078/16-22-3	ST4110206HE0001	—	WHT
C216D22T	M7078/26-22-2	—	—	WHT
C216C24T	M27500-24TG2TN	ST4110[illegible]	—	WHT
C216B24T	M27500-24TG2TN	" (BF)	—	WHT
C216A22T	M7078/26-22-2	—	ST4110206HE0001	WHT
C215C22T	M7078/16-22-3	ST4110206[illegible](BF)	—	BLU
C215B22T	M7078/16-22-3	" (BF)	—	BLU
C215A22T	M7078/16-22-3	ST4110206HE0001	—	BLU
C214C22T	M7078/16-22-3	ST4110206[illegible](BF)	—	BLU
C214B22T	M7078/16-22-3	" (BF)	—	BLU
C214A22T	M7078/16-22-3	ST4110206HE0001	—	BLU
C213C24T	M27500-24TG2TN	ST4110206HE0001(BF)	—	BLU
C213B24T	M27500-24TG2TN	" (BF)	—	BLU
C213A22T	M7078/26-22-2	—	ST4110206HE0001	BLU
C212C24T	M27500-24TG2TN	ST4110206[illegible](BF)	—	WHT
C212B24T	M27500-24TG2TN	" (BF)	—	WHT
C212A22T	M7078/26-22-2	—	ST4110206HE0001	WHT
C211C24T	M27500-24TG2TN	ST4110206[illegible](BF)	—	BLU
C211B24T	M27500-24TG2TN	" (BF)	—	BLU
C211A22T	M7078/26-22-2	—	ST4110206HE0001	BLU
C210A22T	M7078/16-22-2	—	—	WHT
C209A22T	M7078/16-22-2	—	—	WHT
C208A22T	M7078/16-22-2	—	—	BLU
C207A22T	M7078/16-22-2	—	—	BLU
C206D22T	M7078/26-22-2	—	—	BLU
C206C24T	M27500-24TG2TN	ST4110206[illegible](BF)	—	BLU
C206B24T	M27500-24TG2TN	" (BF)	—	BLU
C206A22T	M7078/26-22-2	—	ST4110206HE0001	BLU
C205D22T	M7078/26-22-2	—	—	WHT
C205C24T	M27500-24TG2TN	ST4110206[illegible](BF)	—	WHT
C205B24T	M27500-24TG2TN	" (BF)	—	WHT
C205A22T	M7078/26-22-2	—	ST4110206HE0001	WHT
C204A22T	M7078/16-22-2	—	—	WHT
C203A22T	M7078/16-22-2	—	—	WHT
C202A22T	M7078/16-22-2	—	—	BLU
C201A22T	M7078/16-22-2	—	—	BLU
C200C24T	M27500-24TG2TN	ST4110206[illegible](BF)	—	BLU
C200B24T	M27500-24TG2TN	" (BF)	—	BLU
C200A22T	M7078/26-22-2	—	ST4110206HE0001	BLU

ADD WIRE LIST

1

REVISIONS					
ZONE	LTR	DESCRIPTION		DATE	APPROVED
		1 MAY BE REWORKED 2 CANNOT BE REWORKED 3 RECORD CHANGE 4 NON SHOP PRACTICE 5 PARTS MADE ON			
H	A	SEE SHEET 1 FOR REVISIONS		2-9-79	

AWG	COLOR
	–
	–
	–
	–
	–
…46E0001	–
…1-15	
…1-15	
…1-15	–
	ORN
	ORN
	ORN
	WHT
	WHT
	WHT
	WHT
	WHT
	WHT
…0001	WHT
	ORN
	ORN
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	WHT
	WHT
	WHT
	WHT
…46E0001	WHT
	BLU
	BLU
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…0001	BLU
	WHT
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…0001	WHT
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	WHT
…0001	WHT
	WHT
	WHT
	BLU
	BLU
	BLU
	BLU
…0001	BLU

H G F E D C A

A 8691-546606

Rockwell International Corporation Columbus Aircraft Division Columbus, Ohio 43216	SIZE	FSCM NO	
DRN BY	J	89372	8691-546606
DATE 2-9-79	SCALE		SHEET 3

FORM 311-B-31 REV 8-78

FIG. 5

5.1.4 System Checkout

Procedure details are given in Appendix C. A pressure of 25 psig was applied to the T-2C reservoir. With electrical power on the aircraft, the motor/pump unit was energized. The cockpit gage was observed to read 8000 psig (55 MPa). Operation of the 8000 psi (55MPa) hydraulic system was satisfactory; no malfunctions or leaks occurred.

Force was alternately applied to the rudder pedals in both the DFBW and ABU modes. The proper rudder deflections were visually monitored and the corresponding voltages and Light Emitter Diode (LED) indications verified on the AFCAS test box.

Rudder control was smooth and positive. A small amount of hysteresis was noted due to normal friction in the cables, pulleys, and bellcranks used in the T-2C directional system as follows:

Dead band at 0° rudder

- With cable/pulley friction (no pedal corrections) ———————— 1°
- with cable/pulley friction minimized (pedals alternately tapped lightly)——— 1/4°

No problems were encountered with the foregoing steps, and all of the data were satisfactory.

5.2 INSTRUMENTATION

5.2.1 Description

The T-2C was equipped with several flight data acquisition systems. Two were used in the digital AFCAS program: (1) an 18 channel telemetry system, and (2) a 21 hole photo recorder system. The telemetry oscillator package was located in the aft cockpit seat and the photo recorder panel, Figure 5-2, was installed in the nose.

Telemetry data were recorded at the NAAD-C Telemetry and Data Processing Center, Figure 5-3, where a UHF receiving/tracking system provided real-time data acquisition and direct read-out on strip charts. Audio communication with the pilot was available for convenience and safety monitoring.

Pilot instrumentation controls were located above the cockpit instrument panel, Figure 5-4, and on the control stick. Data in the two recording systems were related by means of correlator numbers printed on the photo recorder film, and correlator blips on the telemetry (TM) strip chart. A correlator counter could be read by the pilot for reference purposes.

Flight data parameters instrumented in the T-2C for the digital AFCAS program are listed in Appendix C. Operating range, accuracies, and response capabilities are also given.

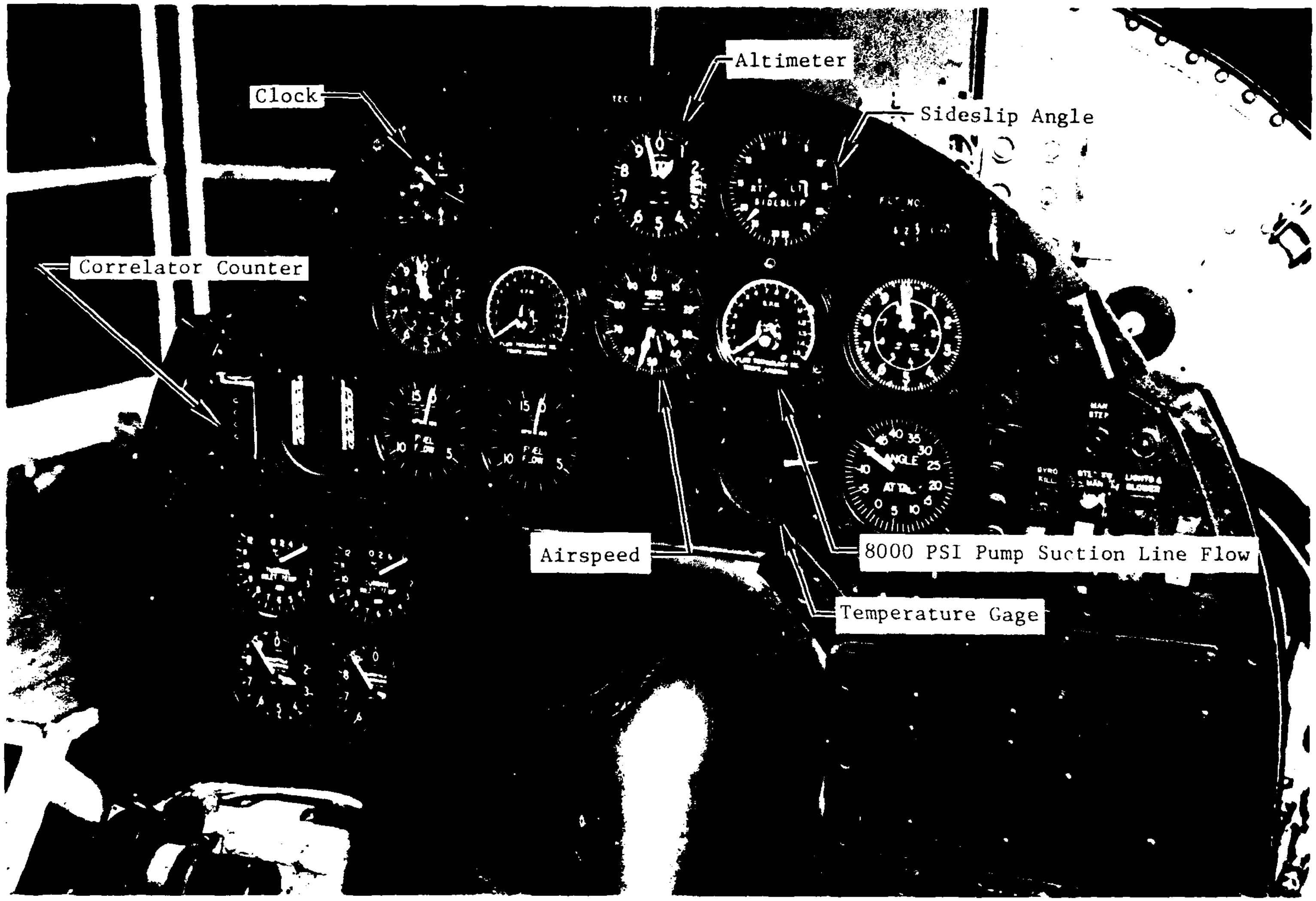

Figure 5-2 Photo Recorder Panel

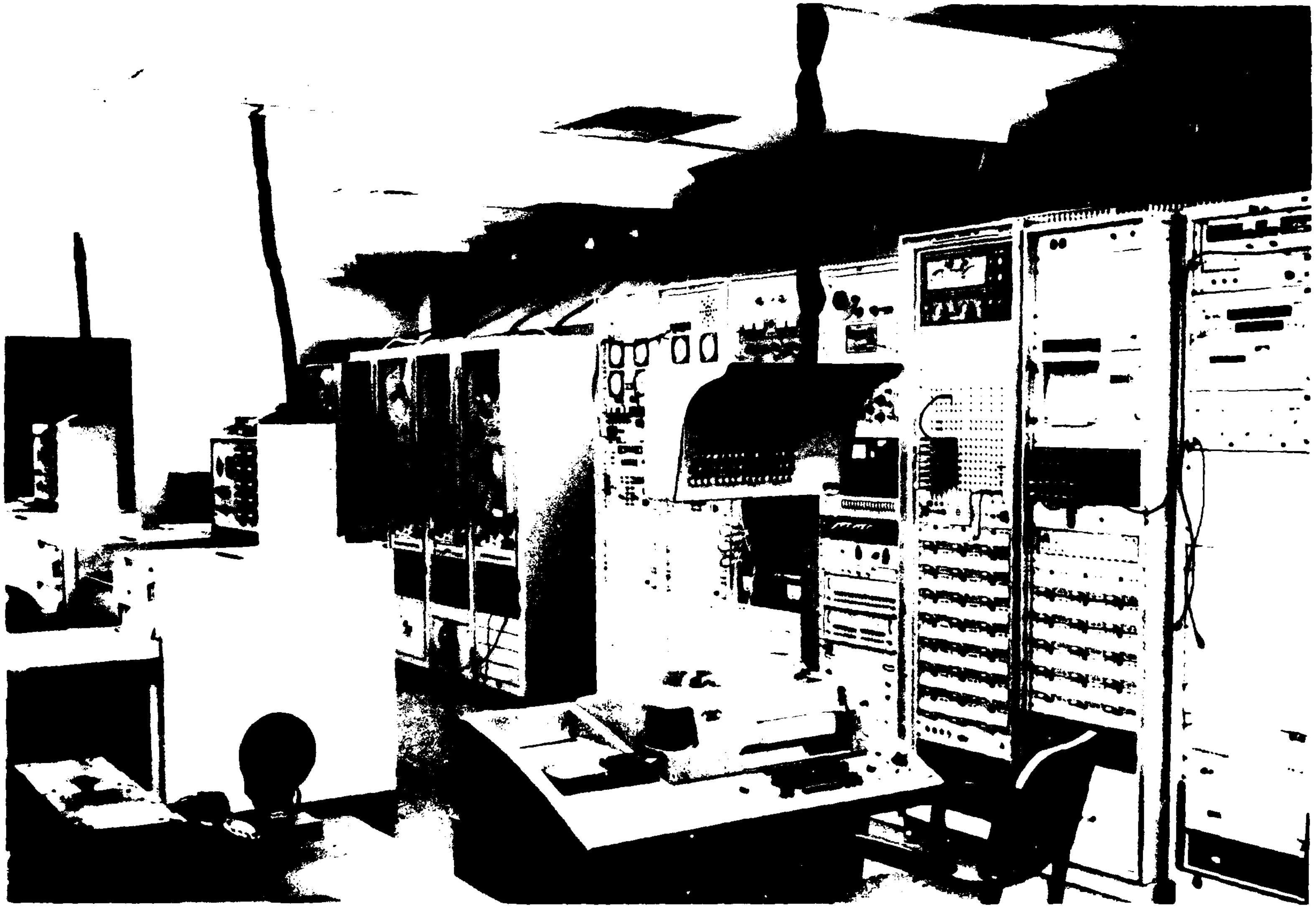

Figure 5-3 Telemetry and Processing Center

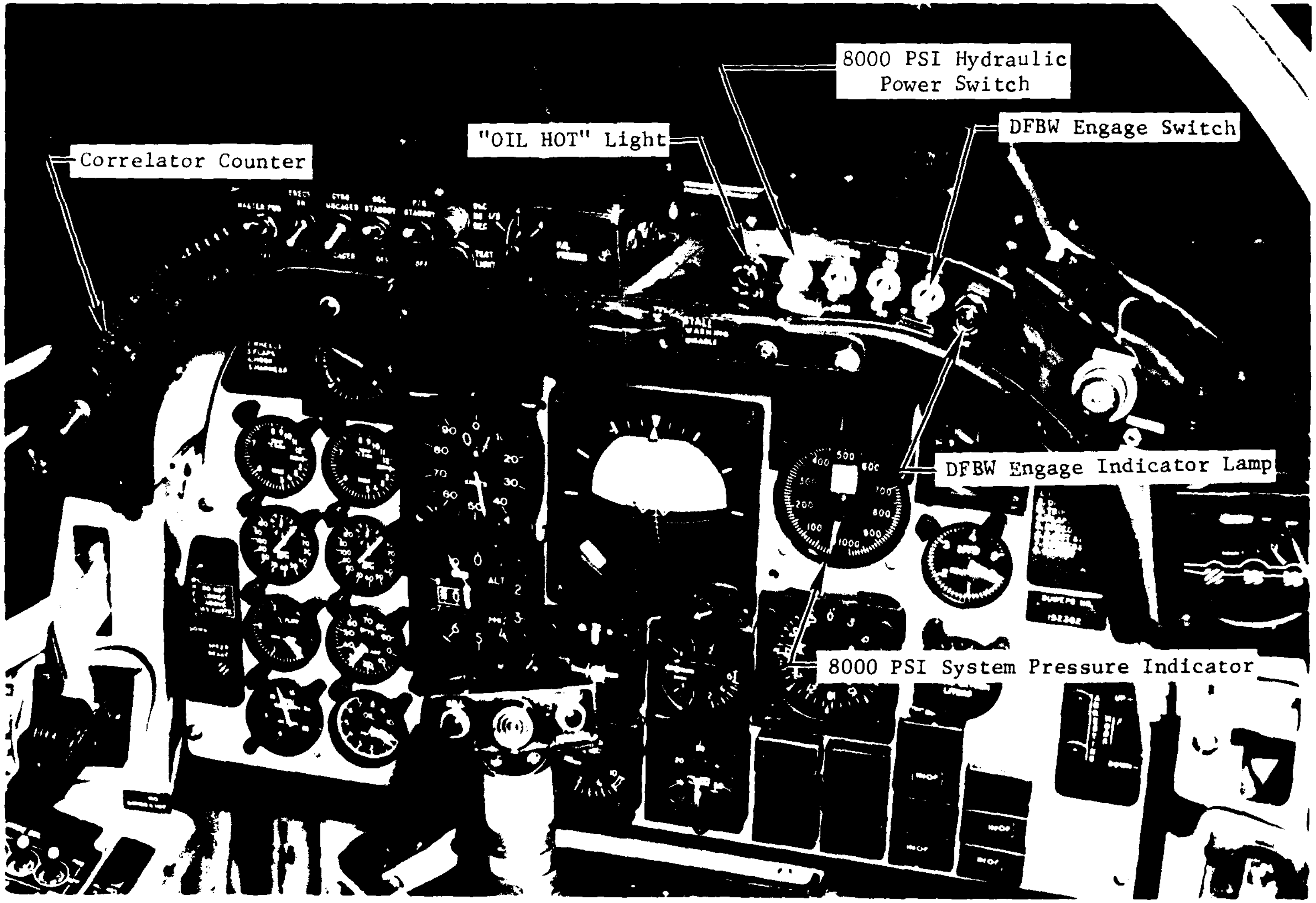

Figure 5-4 Cockpit Instrument Panel

5.2.2 Ground Checkout

Instrumentation operation and parameter calibrations were verified in the hangar and also during a 30-minute ground run in the DFBW mode with the aircraft engines operating. No problems were encountered and all readings were within prescribed limits.

5.3 FLIGHT PLAN

The primary objective of the Flight Test Program was to evaluate performance of the computer-controlled direct digital fly-by-wire characteristics of the AFCAS in a T-2C aircraft. Approximately three flight hours were expected to be sufficient to evaluate performance, confirm prior analyses and laboratory tests, and provide a measure of confidence in system reliability.

The flight plan was designed to determine digital control characteristics at altitudes up to 30,000 feet (9.1 Km) and speeds up to 340 knots (175 m/sec.) and to compare performance between the DFBW and ABU modes of operation.

Details of the flight plan are included in Appendix C.

5.4 FLIGHT TEST RESULTS

Three flights were flown for a total of 4.7 hours. The pilot stated that performance of the Direct Digital Drive AFCAS test installation was completely satisfactory. No difference in "feel" was noted between the DFBW and ABU modes of operation. Additional pilot comments were similar to those listed in the Phase V AFCAS flight test program contained in Reference 5, and included:

- Directional Control Response was judged to be superior to the production T-2C.

- Pilot adaptation to "force control" of the rudder was quickly and easily acquired.

- The fixed pedals provide full rudder and allow much easier braking (in combination) without severe leg and foot extension that is required for conventional deflection controls.

- Hydraulic system fluid pressure and temperatures were normal.

- No malfunctions occurred.

5.4.1 Flight Program Summary

Following is a summary of the Direct Digital Drive AFCAS flight program:

FLIGHT	MAX. AIR SPEED & ALTITUDE	NZ	DURATION
1	250 KOAS & 20,000 FT.	3.0"g"	1.4 Hours
2	250 KOAS & 20,000 FT.	3.0"g"	1.5 Hours
3	340 KOAS & 30,000 FT.	5.5"g"	1.8 Hours

5.4.2 Telemetry Instrumentation Data

Figures 5-5A through 5-8B are samples of instrumentation telemetry data covering various tests and maneuvers, recorded during the three test flights.

Rudder kicks, for both DFBW and ABU modes, are shown in Figures 5-5A and 5-5B and demonstrate that damping was dead beat and rudder re-centering was rapid and accurate.

Responses to step inputs and sideslip maneuvers are shown in Figures 5-6A and 5-6B (DFBW mode) and Figures 5-7A and 5-7B (ABU mode), and demonstrate minimum overshoot and rapid response to command inputs.

Landing data, in the DFBW mode, is presented in Figures 5-8A and 5-8B.

5.4.3 Photo Recorder Instrumentation Temperature Data

Table III contains Photo Recorder Flight Temperature Data, listing maximum and minimum temperatures for six thermocouple locations during the three test flights. All temperatures were within normal operating limits.

TABLE III
PHOTO RECORDER FLIGHT TEMPERATURE DATA, °C

LOCATION	FLT. #1 MIN.	FLT. #1 MAX.	FLT. #2 MIN.	FLT. #2 MAX.	FLT. #3 MIN.	FLT. #3 MAX.
Heat Exchanger Outlet Hydraulic Fluid	36	91	22	93	36	81
Heat Exchanger Inlet Hydraulic Fluid	52	102	41	103	52	98
Electronic Drive Unit Housing	16	26	16	276	4	32
Pump Case Drain Hydraulic Fluid	59	104	49	105	58	100
Pump, Suction, Hydraulic Fluid	26	69	21	71	29	65
Fuselage Compartment Ambient Air	22	32	10	29	-3	38

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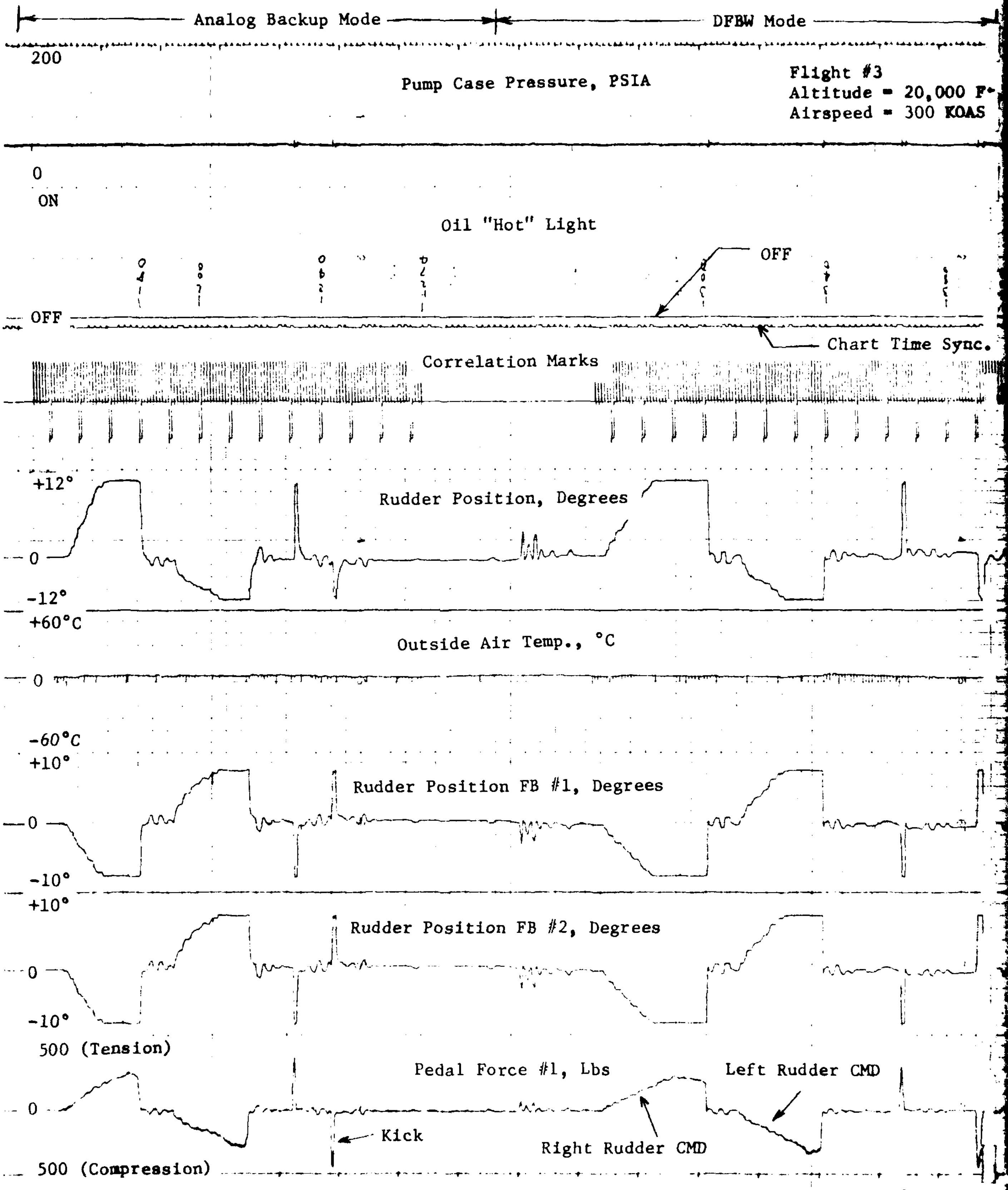

Figure 5-5A Instrumentation Data, Sideslip & Kick Inputs, Digital Fly-By-Wire & Analog Back-Up Modes

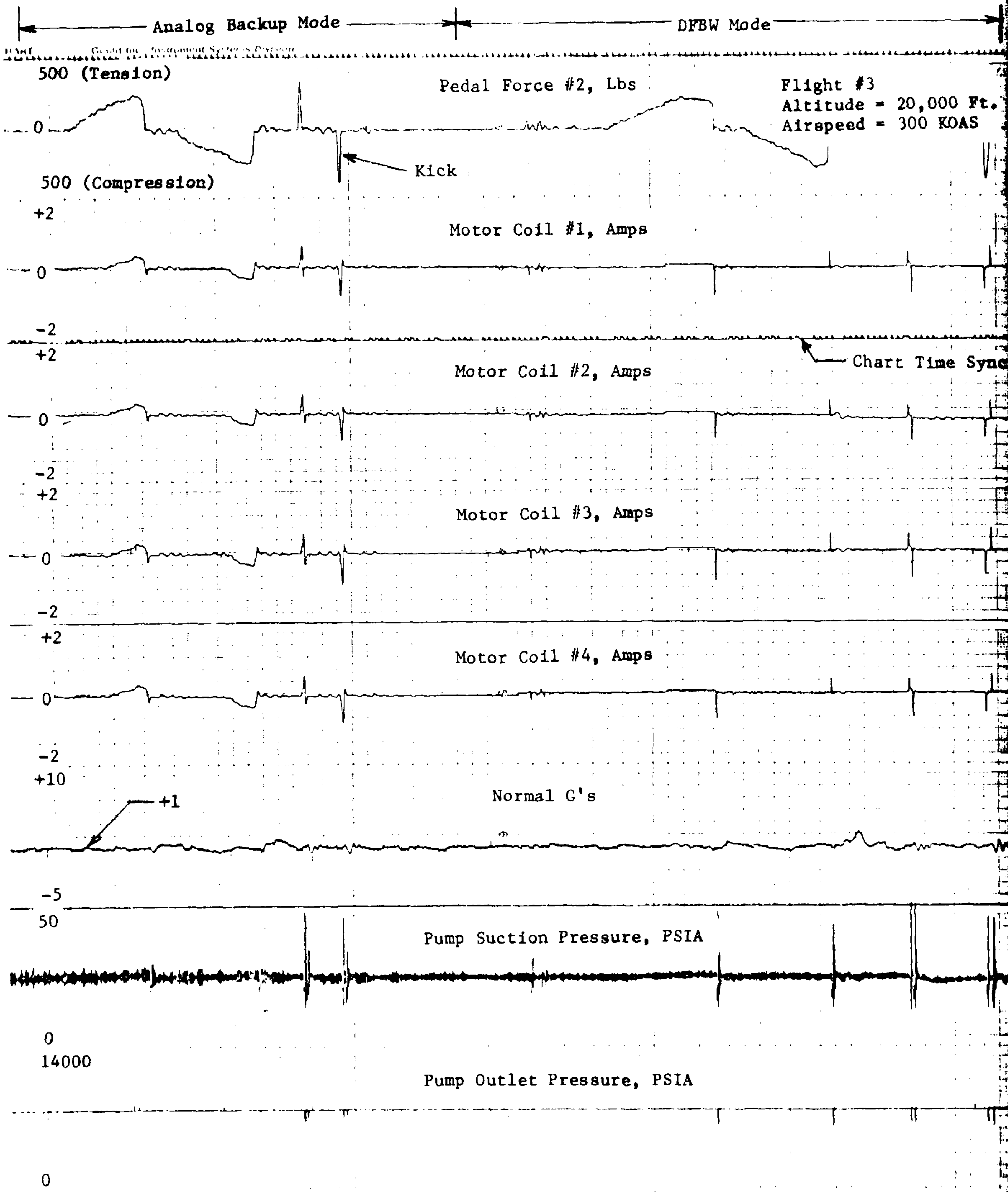

Figure 5-5B Instrumentation Data, Sideslip & Kick Inputs, Digital Fly-By-Wire and Analog Back-Up Modes

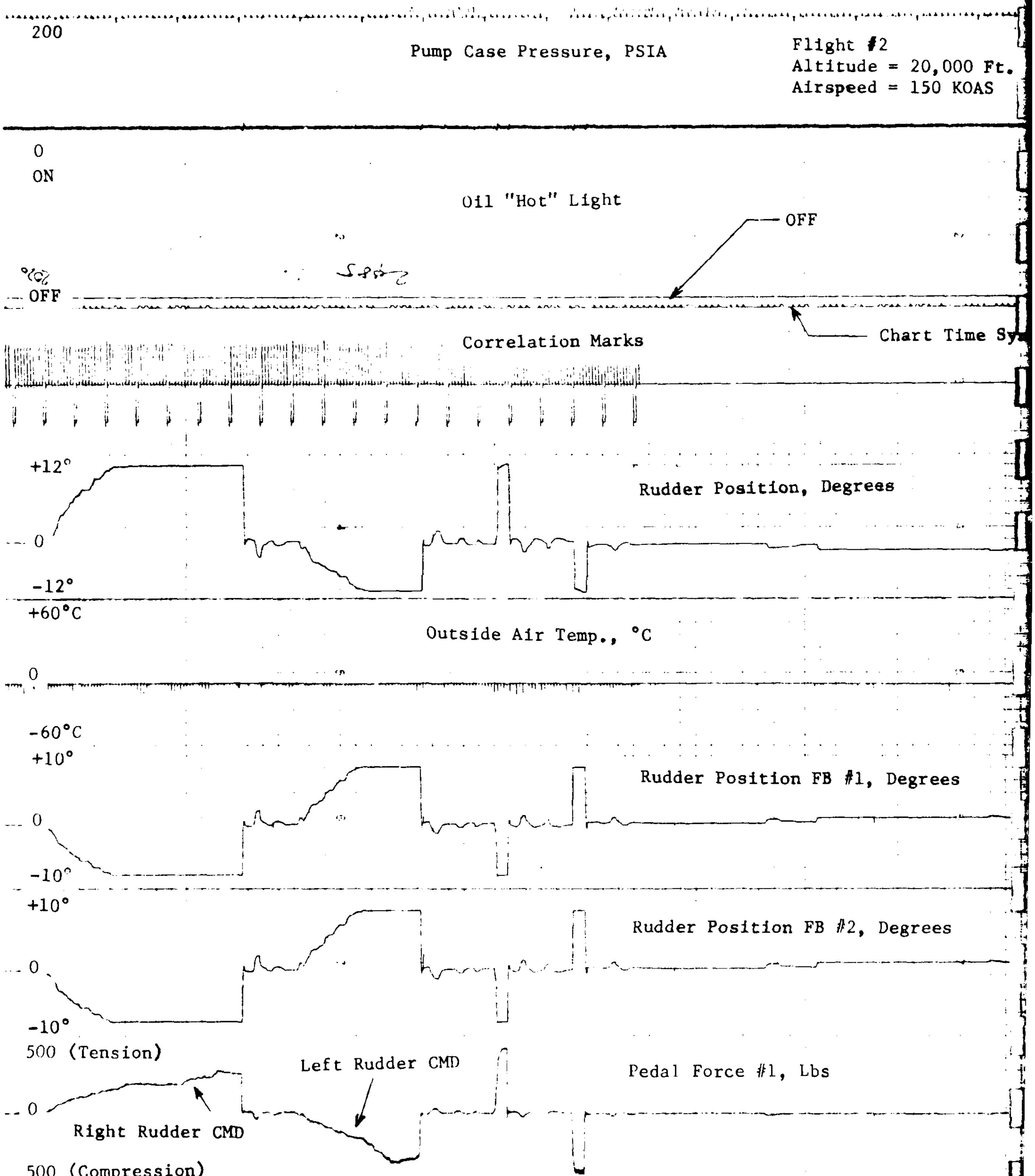

Figure 5-6A Instrumentation Data, Sideslip & Step Input, Digital Fly-By-Wire Mode

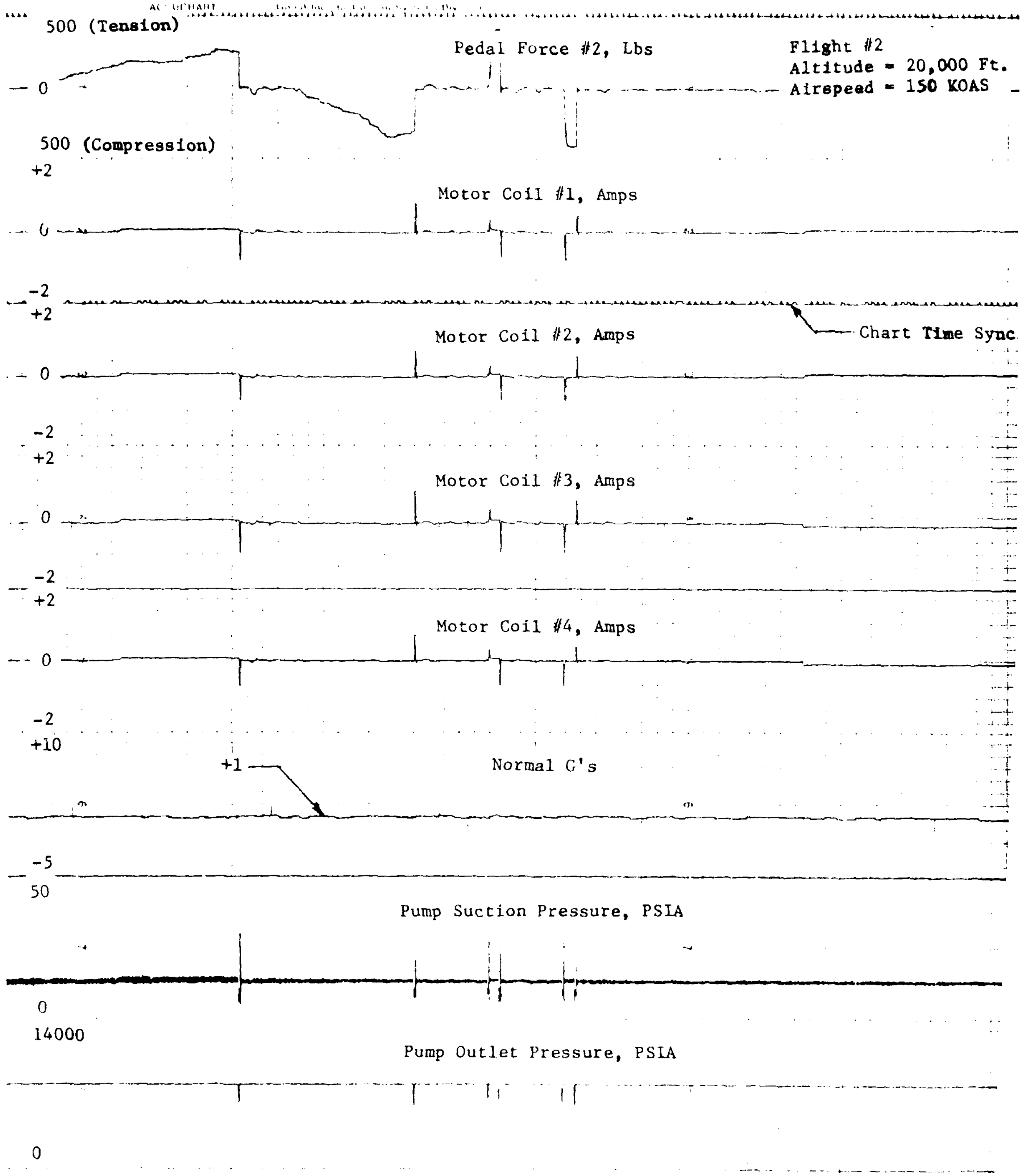

Figure 5-6B Instrumentation Data, Sideslip & Step Inputs, Digital Fly-By-Wire Mode

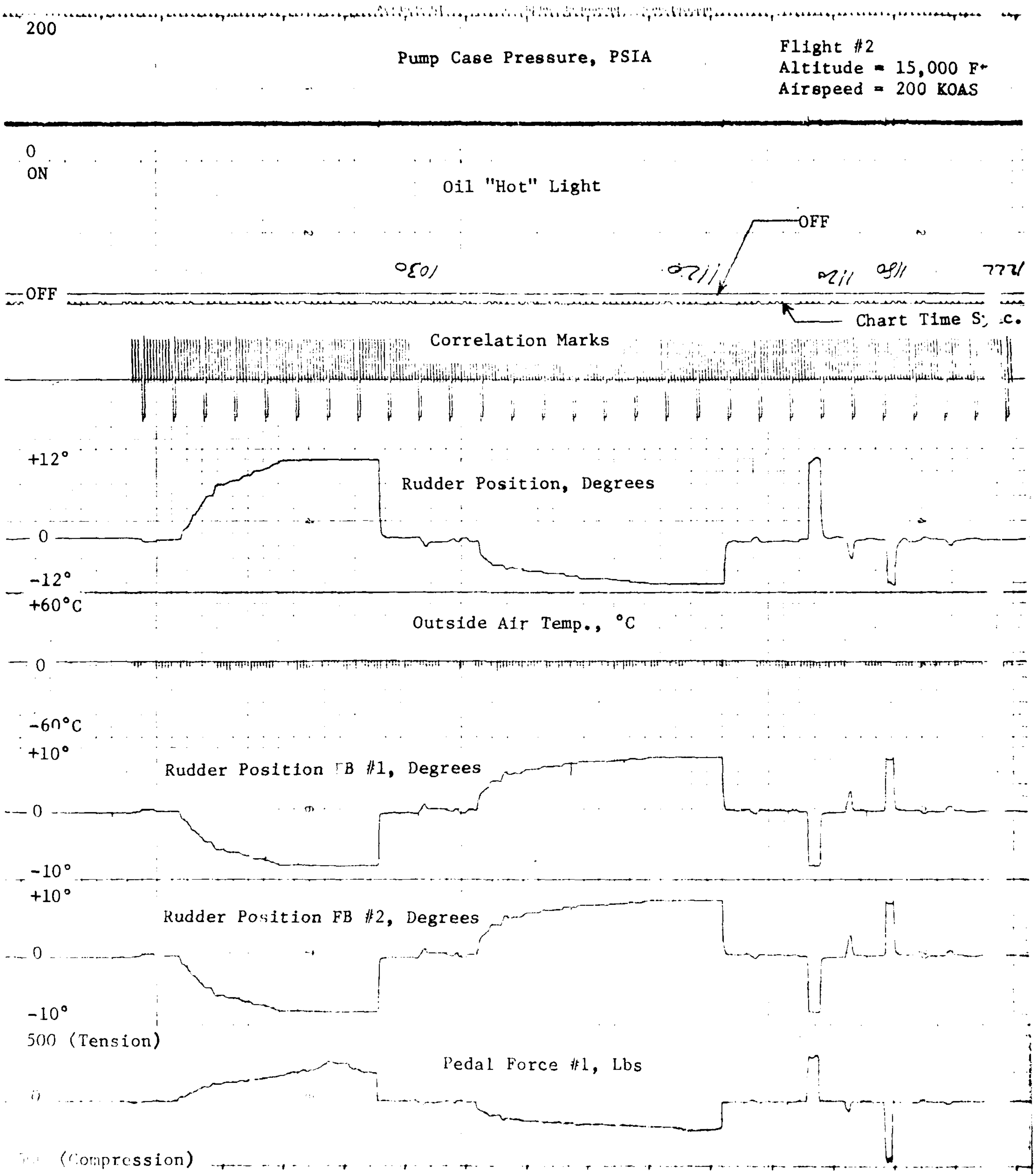

Figure 5-7A Instrumentation Data, Sideslip & Step Inputs, Analog Back-Up Mode

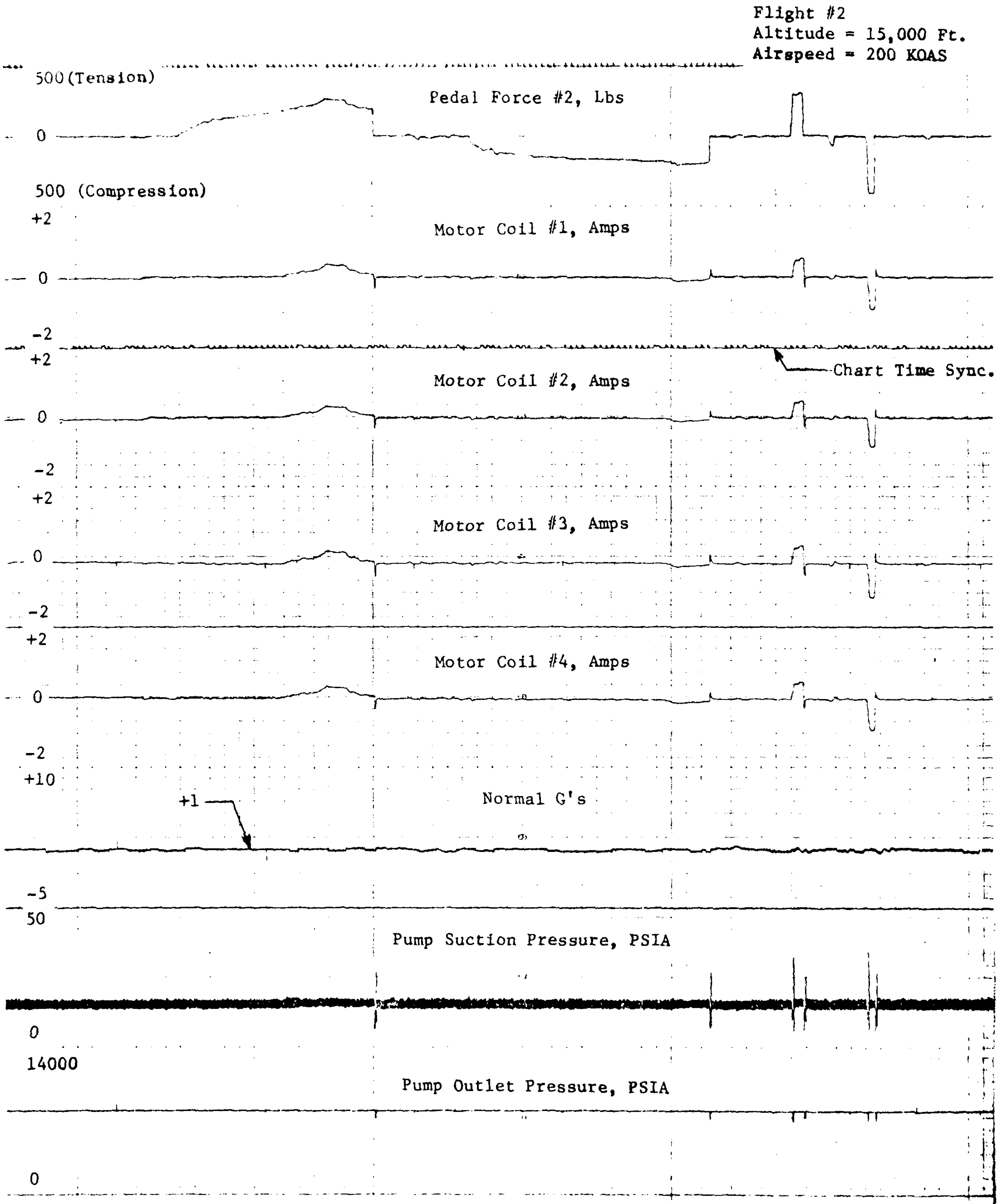

Figure 5-7B Instrumentation Data, Sideslip & Step Inputs, Analog Back-Up Mode

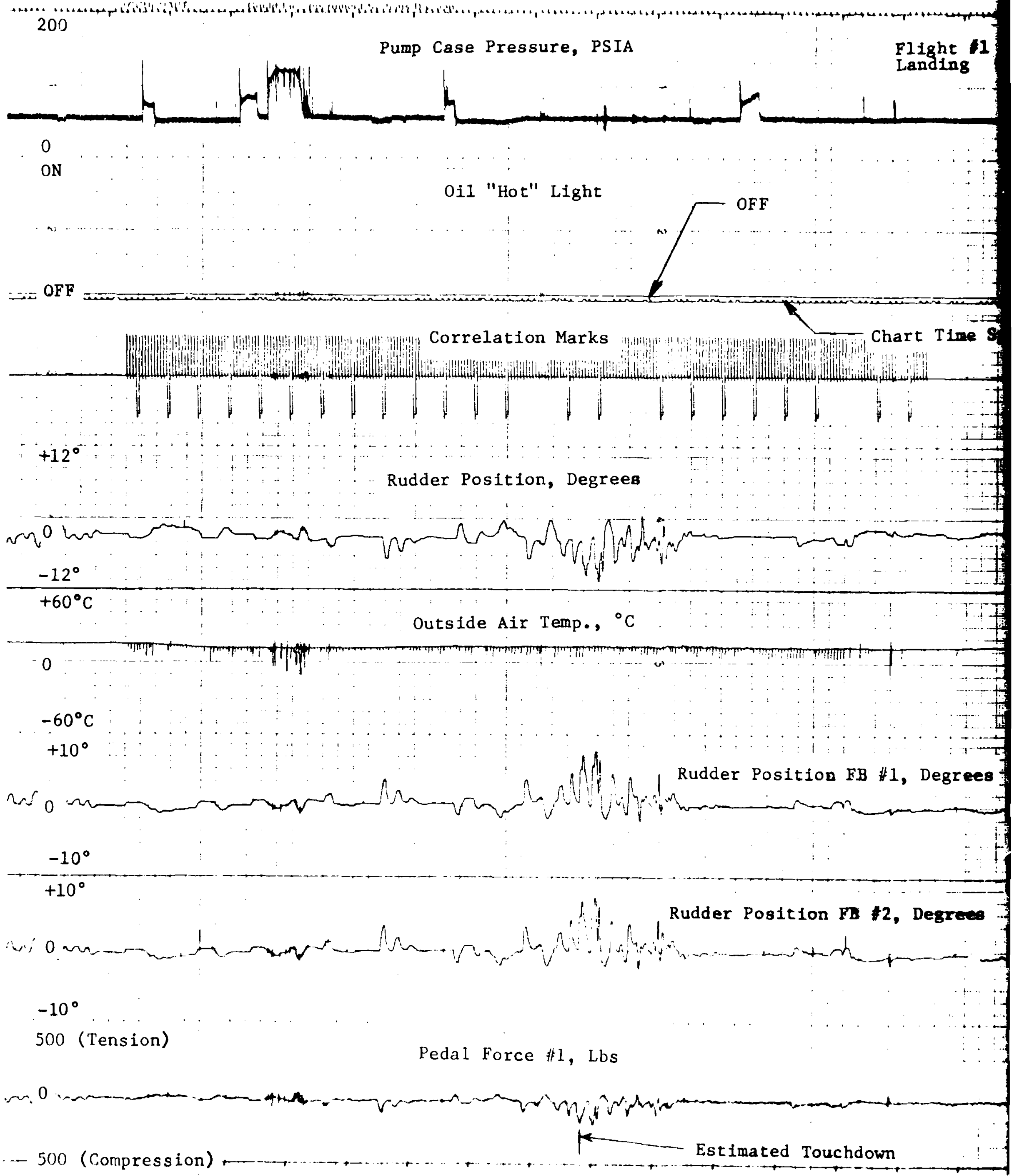

Figure 5-8A Instrumentation Data, Landing, Digital Fly-By-Wire Mode

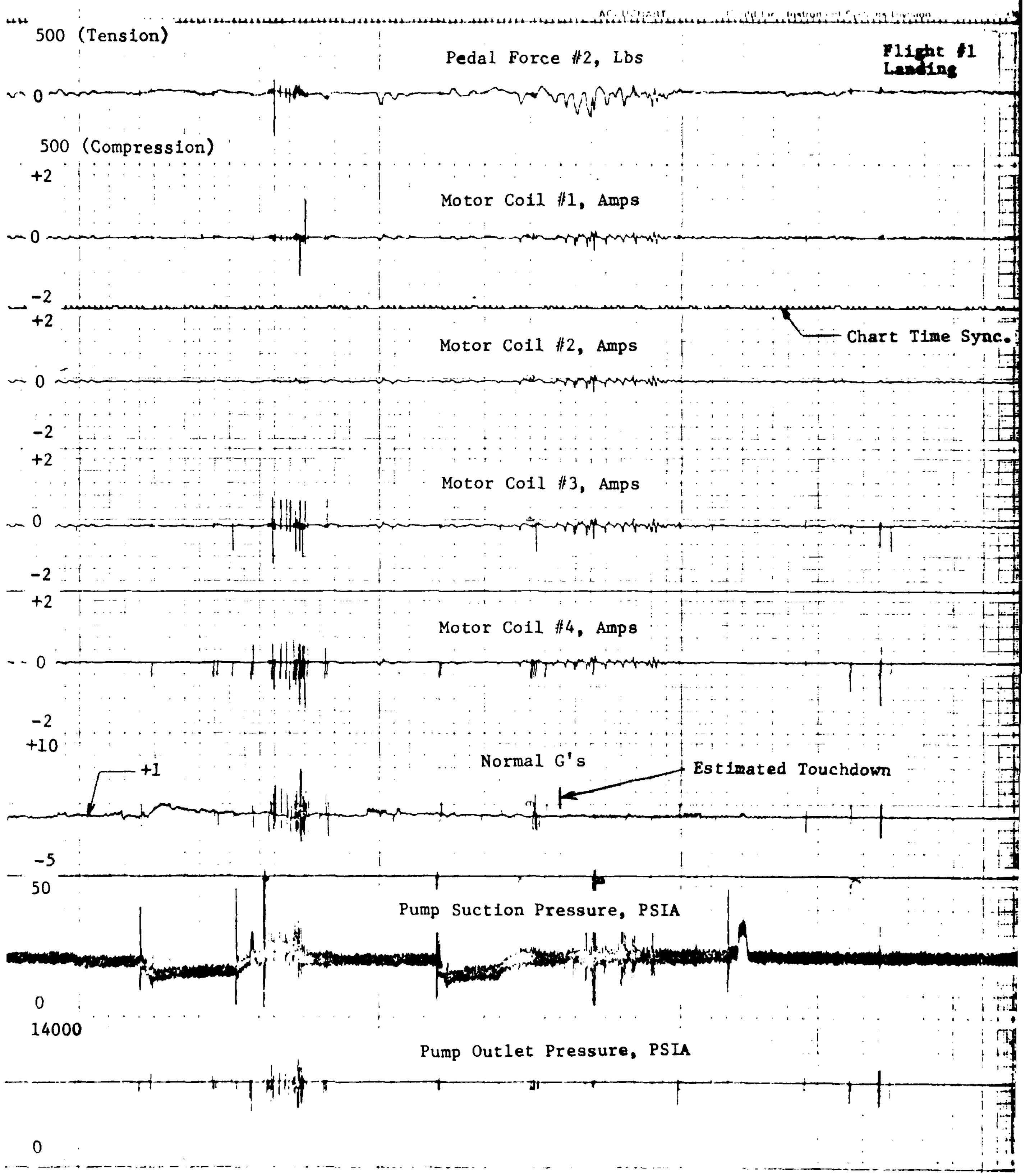

Figure 5-8B Instrumentation Data, Landing, Digital Fly-By-Wire Mode

6.0 RECOMMENDATIONS

The digital drive concept for a direct drive actuator was successfully demonstrated in the laboratory and in flight during Phase VI of the direct-drive actuator study (the subject of this report). Pulse modulated signals, generated in the microcomputer, were power amplified in a Class A analog amplifier EDU which is suitable for either analog or digital control of the direct drive surface actuator. Laboratory tests were performed in both modes of operation.

A company funded effort at Rockwell designed and tested a power stage to operate with a pulse modulated drive signal. This design, described in Appendix D, produced a circuit that reduces power dissipation by a factor of ten and results in a major decrease in amplifier size. The logical next step to the Phase VI program would be to develop and test an EDU as an integral part of the actuator.

Two programs are already underway that could utilize the electronics integrated into a direct drive actuator. These are: (1) Direct Drive Valve (DIDR) Development Program and (2) Hydra-Optical Flight Control Actuation System (HOFCAS). A digital EDU could be utilized advantageously with both of these programs by reducing the drive power requirements and providing electronics that would mount directly on the direct drive valve.

The following tasks are recommended as logical next steps in the AFCAS development cycle:

INTEGRATED ELECTRONIC CONTROL FOR AFCAS

Task 1. Develop Integrated Electronic Circuits for Direct Digital Control of AFCAS

Task 2. Procure a High Temperature Integrated Digital Drive Electronics for AFCAS

Task 3. Integrate and test the Digital Drive Electronics and a Direct Drive Valve with AFCAS

Task 4. Install and Flight Test the Integrated Actuator in a T-2C Aircraft

A second recommendation is the development of a feedback sensor that can be integrated directly into the direct drive actuator. The Phase VI AFCAS program demonstrated the direct digital control of a surface actuator. HOFCAS will demonstrate that the surface can be optically controlled through self contained power. Effort is still required on the feedback sensor design. Navy programs are underway to develop optical sensors; however, these are still in the conceptual stage and the sensors are quite large. Additional concepts that permit the sensor to be contained inside the actuator to protect it from the physical and electrical environment need to be explored.

REFERENCES

Reference No.

1. NR72H-240, Feasibility Study for Advanced Flight Control Actuation System (AFCAS), Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-72-C-0108, June 1972, Unclassified. AD 767 058

2. NR73H-107, Control-By-Wire Actuator Model Development for AFCAS, Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-73-C-0405, January 1974, Unclassified. AD 772 588

3. NR75H-1, Control-By-Wire Modular Actuator Tests (AFCAS), Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-73-C-0405, January 1975, Unclassified. AD A-006 371

4. NR76H-1, Design and Fabrication of an 8000 psi Control-By-Wire Actuator for Flight Testing in a T-2C Airplane, Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-75-C-0311, January 1976, Unclassified. AD-A024 487/IGT

5. J. N. Demarchi and R. K. Haning, Flight Verification of the Advanced Flight Control Actuation System (AFCAS) In the T-2C Aircraft, NAVAIRDEVCEN 75287-60, Columbus Aircraft Division, Rockwell International Corporation, Contract N62269-76-C-0201, June 1978, Unclassified.

APPENDIX A

MICROCOMPUTER ASSEMBLY

The microcomputer selected for this program was based on the Motorola MC6800 microprocessor. The assembly consisted primarily of the Motorola Monoboard Microcomputer 1A (Micromodule 1A) which is a complete computer-on-a-board, plus Burr Brown D/A and A/D converters, all mounted on a mother board and housed in a single unit. This unit, shown in Figure A-1, contains all the interfaces and wiring required for the processor and has space for two additional cards for expansion of capability.

The heart of the unit is the monoboard microcomputer which has the following features:

- MC6800 Microprocessing Unit (MPU) with associated clock oscillator, power on reset timer, and memory decoding logic.
- 1024 Bytes of RAM.
- Sockets for up to 4096 bytes of Alterable Read Only Memory (AROM) or mask-programmable ROM (Four of the 2048 x 8-bit ROM's may also be used if the proper jumper connections are made, thus providing over 8K of ROM on this module).
- One RS-232C compatible interface that utilizes a single MC6850 (ACIA).
- Two programmable MC6820 PIA's that provide 40 programmable Input/Output and control lines.
- Address, data, and control bus drivers to interface Monoboard Microcomputer 1A with other modules in the Family or with an EXORciser.
- TTL signal level inputs and TTL signal level, three-state, or open collector outputs.

This monoboard microcomputer is shown in block diagram form in Figure A-2. A photograph of the board is shown in Section 3.7 of the main report. The specification of the monoboard microcomputer is given in Table A-I.

The MPU is contained on a single chip on the board and is the Motorola MC6800 MPU. The organization of the chip is shown in Figure A-3. The complete instruction set is given in Tables A-II, A-III, and A-IV.

The A/D and D/A converters make up the other two boards in the microcomputer assembly. Figure A-4 is a block diagram of the A/D converter. Figure A-5 is a block diagram of the D/A converter.

Table A-V is a summary of the characteristics of the two converters.

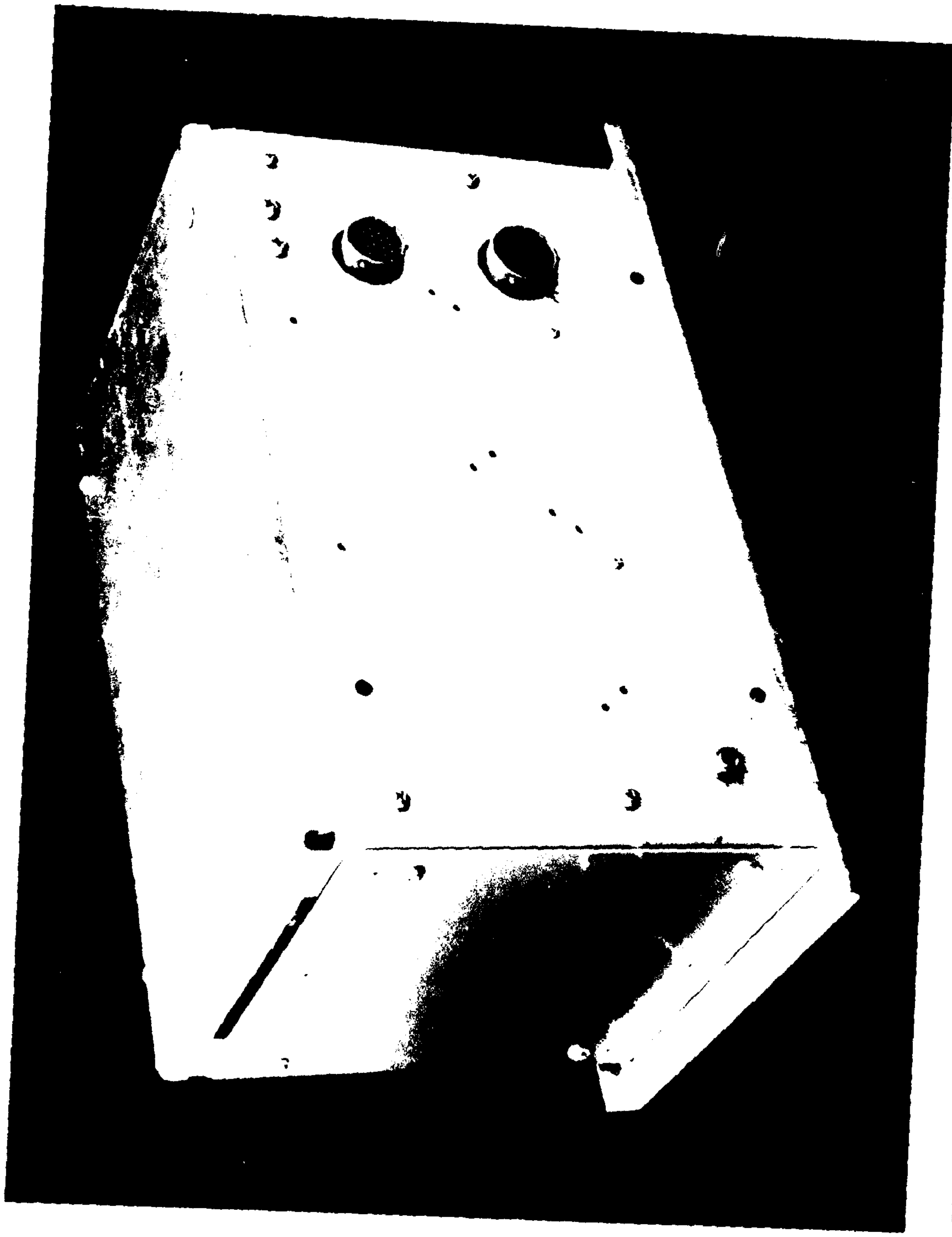

Figure A-1 Motorola Microcomputer Unit

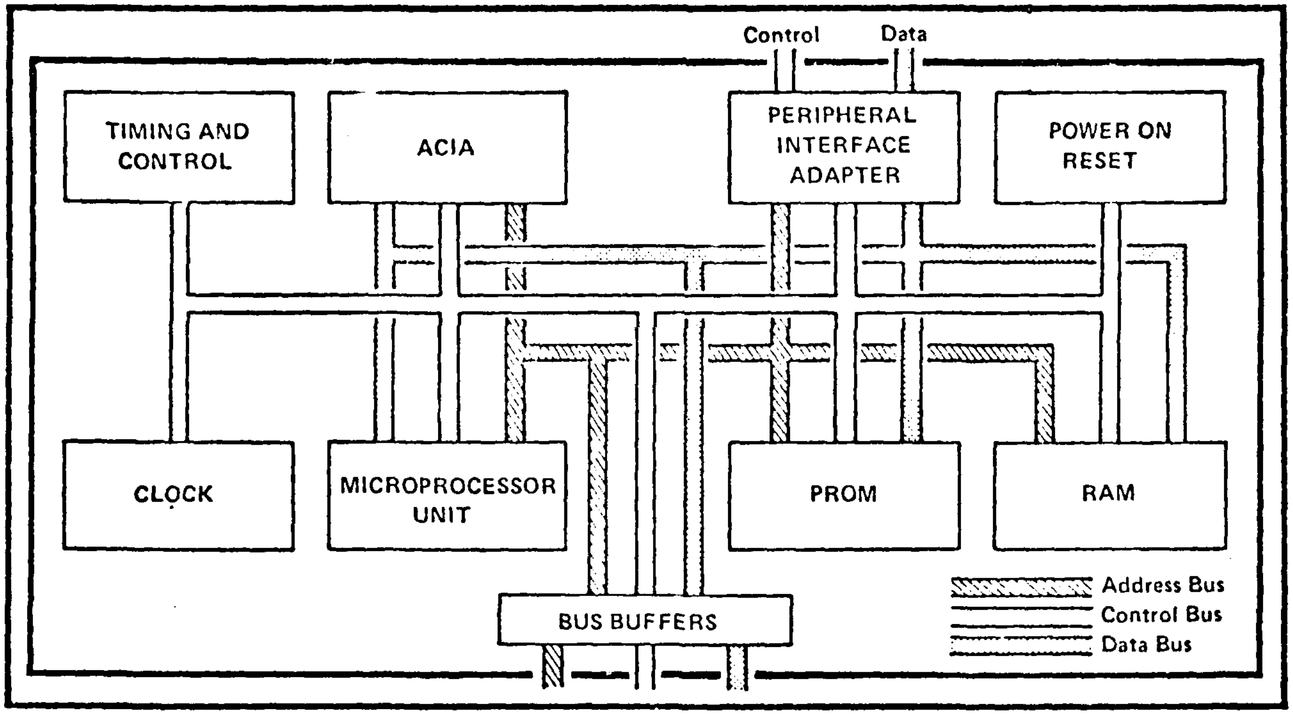

Figure A-2 Monoboard Microcomputer

TABLE A-1

MONOBOARD MICROCOMPUTER 1A SPECIFICATIONS

CHARACTERISTICS	SPECIFICATIONS
MICROPROCESSOR	MC6800 MPU
POWER REQUIREMENTS WITHOUT AROMs/ROMs	+5 VDC AT 1.1A (MAX) +12 VDC AT 20mA (MAX) -12 VDC AT 25mA (MAX)
WITH FOUR AROMs/ROMs	+5 VDC AT 1.3A (MAX) +12 VDC AT 260mA (MAX) -12 VDC AT 180mA (MAX)
WORD SIZE	
DATA	8 BITS
ADDRESS	16 BITS
INSTRUCTIONS	8, 16, OR 24 BITS
INSTRUCTIONS	72 VARIABLE LENGTH INSTRUCTIONS
ADDRESSING MODES	SEVEN ADDRESSING MODES: DIRECT, RELATIVE, IMMEDIATE, INDEXED, EXTENDED, IMPLIED, AND ACCUMULATOR
CLOCK SIGNAL	CRYSTAL CONTROLLED 1 MHz WITH CAPABILITY TO WORK WITH DYNAMIC MEMORIES
MEMORY SIZE CAPABILITY	
ROM/PROM MEMORY (ON BOARD)	4K BYTES OF MEMORY (SOCKETS ONLY)
RAM (ON BOARD)	1K BYTE OF MEMORY
I/O ADDRESSING (ON BOARD)	2 MC6820 PIA 32 DATA LINES 8 INTERRUPT/CONTROL LINES 1 MC6850 ACIA 2 DATA LINES 5 CONTROL LINES
EXTERNAL MEMORY	59K BYTES AVAILABLE FOR EXTERNAL MEMORY AND I/O WHEN FOUR 1K AROM/ROMs ARE USED. THIS IS REDUCED TO 55K BYTES IF FOUR 2K ROMs ARE USED
INPUTS	
INTERNAL	$\overline{\text{IRQ}}$ MASKABLE INTERRUPT FROM PIAs AND ACIA
EXTERNAL	$\overline{\text{IRQ}}$ MASKABLE INTERRUPT AND $\overline{\text{NMI}}$ NON-MASKABLE INTERRUPT.

TABLE A-1 (CONTINUED)

CHARACTERISTICS	SPECIFICATIONS
PIAI INTERFACE SIGNALS	
CA1	TTL VOLTAGE COMPATIBLE INTERRUPT INPUT WITH PROGRAMMABLE ACTIVE TRANSITION
CA2	TTL VOLTAGE COMPATIBLE LINE; PROGRAMMABLE TO ACT AS AN INTERRUPT INPUT OR AS A PERIPHERAL CONTROL OUTPUT
PAO-PA7	EIGHT TTL VOLTAGE COMPATIBLE DATA LINES THAT CAN BE PROGRAMMED TO FUNCTION AS INPUTS OR OUTPUTS
CB1	TTL VOLTAGE COMPATIBLE INTERRUPT INPUT WITH PROGRAMMABLE ACTIVE TRANSITION
CB2	TTL VOLTAGE COMPATIBLE LINE; PROGRAMMABLE TO ACT AS AN INTERRUPT INPUT OR AS A PERIPHERAL CONTROL OUTPUT.
PBO-PB7	EIGHT TTL VOLTAGE COMPATIBLE DATA LINES THAT CAN BE PROGRAMMED TO FUNCTION AS INPUTS OR OUTPUTS
PIA2 INTERFACE SIGNALS	
CA1	TTL VOLTAGE COMPATIBLE INTERRUPT INPUT WITH PROGRAMMABLE ACTIVE TRANSITION
CA2	TTL VOLTAGE COMPATIBLE LINE; PROGRAMMABLE TO ACT AS AN INTERRUPT INPUT OR AS A PERIPHERAL CONTROL OUTPUT
PAO-PA-7	EIGHT TTL VOLTAGE COMPATIBLE DATA LINES THAT CAN BE PROGRAMMED TO FUNCTION AS INPUTS OR OUTPUTS
CB1	TTL VOLTAGE COMPATIBLE INTERRUPT INPUT WITH PROGRAMMABLE ACTIVE TRANSITION
CB2	TTL VOLTAGE COMPATIBLE LINE; PROGRAMMABLE TO ACT AS AN INTERRUPT INPUT OR AS A PERPHERAL CONTROL OUTPUT
PBO-PB7	EIGHT TTL VOLTAGE COMPATIBLE DATA LINES THAT CAN BE PROGRAMMED TO FUNCTION AS INPUTS OR OUTPUTS
ACIA INTERFACE SIGNALS	
TAX DATA	RS-232C COMPATIBLE SERIAL DATA INPUT LINE ($\pm$30 VDC INPUT SIGNAL RANGE).

TABLE A-1(CONTINUED)

CHARACTERISTICS	SPECIFICATIONS
RX DATA	RS-232C COMPATIBLE SERIAL DATA OUTPUT LINE (± 10mA CURRENT LIMITED OUTPUT)
RTS	RS-232C COMPATIBLE OUTPUT CONTROL LINE ENABLED BY INSTALLING JUMPER CONNECTION BETWEEN TERMINALS E6 AND E7 (±10mA CURRENT LIMITED OUTPUT)
CTS/DSR	RS-232C COMPATIBLE OUTPUT CONTROL LINE (±10mA CURRENT LIMITED OUTPUT)
DTA TERM RDY	RS-232C COMPATIBLE INPUT CONTROL LINE (±30 VDC INPUT SIGNAL RANGE)
SIG DET	RS-232C COMPATIBLE OUTPUT CONTROL LINE (±10mA CURRENT LIMITED OUTPUT). THIS LINE CAN ALSO BE CHANGED TO AN INPUT BY REMOVING THE JUMPER BETWEEN TERMINALS E8 AND E9 AND INSTALLING THE JUMPER BETWEEN TERMINALS E9 AND E10. THIS LINE THEN BECOMES AN RS-232C COMPATIBLE INPUT CONTROL LINE (±30 VDC INPUT SIGNAL RANGE)
LINE TERMINATORS (CB1, CB2, AND PB0-PB7 ON BOTH PIAs)	10K OHM PULL-UP RESISTORS
OPERATING TEMPERATURE	0° TO 70°C
PHYSICAL CHARACTERISTICS WIDTH X HEIGHT	9.75 IN. x 6.15 IN.
BOARD THICKNESS	0.062 IN.
BUS MATING CONNECTOR TYPES CONNECTOR P1 (86 PIN)	STANFORD APPLIED ENGINEERING SAC-43D/1-2 OR EQUIVALENT
CONNECTORS P2 AND P4 (50 PIN)	3M TYPE 3415-0001 OR EQUIVALENT
CONNECTOR P3 (20 PIN)	3M TYPE 3461-0001 OR EQUIVALENT

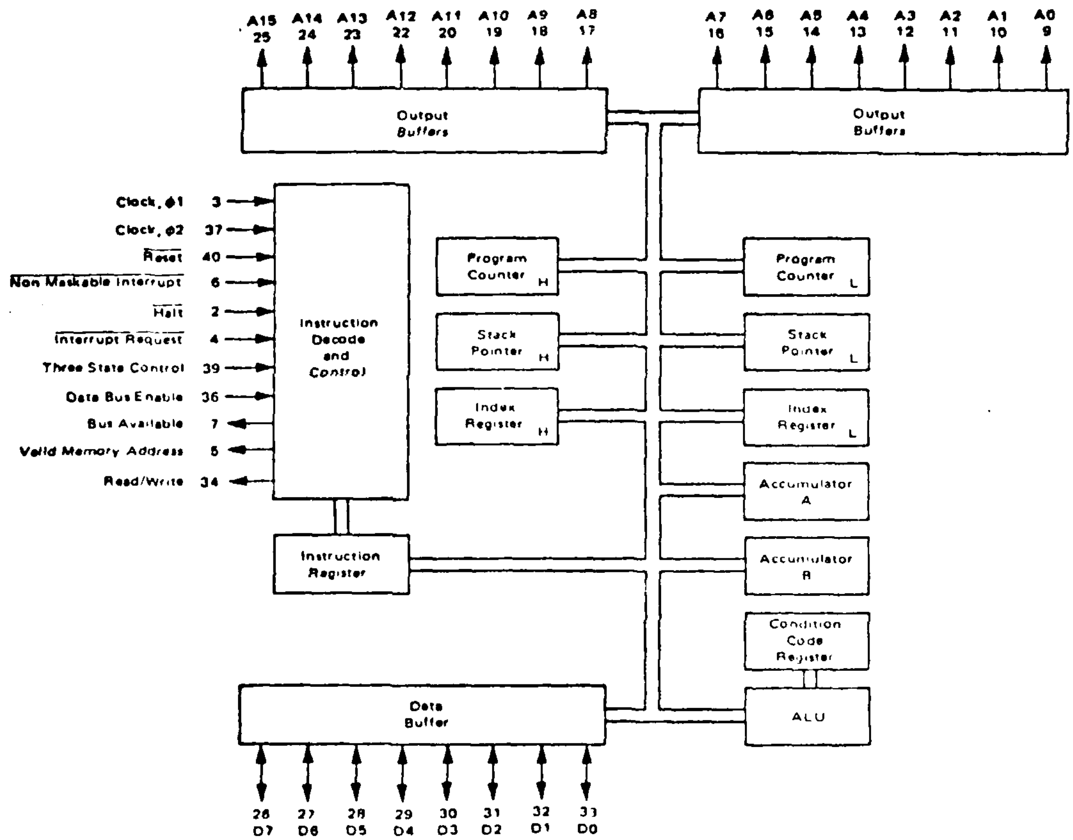

Figure A-3 Microprocessor Unit Organization (MC 6800)

Table A-II Accumulator and Memory Instructions (MC 6800)

OPERATIONS	MNEMONIC	IMMED OP	IMMED ~	IMMED #	DIRECT OP	DIRECT ~	DIRECT #	INDEX OP	INDEX ~	INDEX #	EXTND OP	EXTND ~	EXTND #	IMPLIED OP	IMPLIED ~	IMPLIED #	BOOLEAN/ARITHMETIC OPERATION (All register labels refer to contents)	H	I	N	Z	V	C
Add	ADDA	8B	2	2	9B	3	2	AB	5	2	BB	4	3				A + M → A	↕	●	↕	↕	↕	↕
	ADDB	CB	2	2	DB	3	2	EB	5	2	FB	4	3				B + M → B	↕	●	↕	↕	↕	↕
Add Acmltrs	ABA													1B	2	1	A + B → A	↕	●	↕	↕	↕	↕
Add with Carry	ADCA	89	2	2	99	3	2	A9	5	2	B9	4	3				A + M + C → A	↕	●	↕	↕	↕	↕
	ADCB	C9	2	2	D9	3	2	E9	5	2	F9	4	3				B + M + C → B	↕	●	↕	↕	↕	↕
And	ANDA	84	2	2	94	3	2	A4	5	2	B4	4	3				A · M → A	●	●	↕	↕	R	●
	ANDB	C4	2	2	D4	3	2	E4	5	2	F4	4	3				B · M → B	●	●	↕	↕	R	●
Bit Test	BITA	85	2	2	95	3	2	A5	5	2	B5	4	3				A · M	●	●	↕	↕	R	●
	BITB	C5	2	2	D5	3	2	E5	5	2	F5	4	3				B · M	●	●	↕	↕	R	●
Clear	CLR							6F	7	2	7F	6	3				00 → M	●	●	R	S	R	R
	CLRA													4F	2	1	00 → A	●	●	R	S	R	R
	CLRB													5F	2	1	00 → B	●	●	R	S	R	R
Compare	CMPA	81	2	2	91	3	2	A1	5	2	B1	4	3				A − M	●	●	↕	↕	↕	↕
	CMPB	C1	2	2	D1	3	2	E1	5	2	F1	4	3				B − M	●	●	↕	↕	↕	↕
Compare Acmltrs	CBA													11	2	1	A − B	●	●	↕	↕	↕	↕
Complement, 1's	COM							63	7	2	73	6	3				$\bar{M}$ → M	●	●	↕	↕	R	S
	COMA													43	2	1	$\bar{A}$ → A	●	●	↕	↕	R	S
	COMB													53	2	1	$\bar{B}$ → B	●	●	↕	↕	R	S
Complement, 2's (Negate)	NEG							60	7	2	70	6	3				00 − M → M	●	●	↕	↕	①	②
	NEGA													40	2	1	00 − A → A	●	●	↕	↕	①	②
	NEGB													50	2	1	00 − B → B	●	●	↕	↕	①	②
Decimal Adjust, A	DAA													19	2	1	Converts Binary Add. of BCD Characters into BCD Format	●	●	↕	↕	↕	③
Decrement	DEC							6A	7	2	7A	6	3				M − 1 → M	●	●	↕	↕	④	●
	DECA													4A	2	1	A − 1 → A	●	●	↕	↕	④	●
	DECB													5A	2	1	B − 1 → B	●	●	↕	↕	④	●
Exclusive OR	EORA	88	2	2	98	3	2	A8	5	2	B8	4	3				A ⊕ M → A	●	●	↕	↕	R	●
	EORB	C8	2	2	D8	3	2	E8	5	2	F8	4	3				B ⊕ M → B	●	●	↕	↕	R	●
Increment	INC							6C	7	2	7C	6	3				M + 1 → M	●	●	↕	↕	⑤	●
	INCA													4C	2	1	A + 1 → A	●	●	↕	↕	⑤	●
	INCB													5C	2	1	B + 1 → B	●	●	↕	↕	⑤	●
Load Acmltr	LDAA	86	2	2	96	3	2	A6	5	2	B6	4	3				M → A	●	●	↕	↕	R	●
	LDAB	C6	2	2	D6	3	2	E6	5	2	F6	4	3				M → B	●	●	↕	↕	R	●
Or, Inclusive	ORAA	8A	2	2	9A	3	2	AA	5	2	BA	4	3				A + M → A	●	●	↕	↕	R	●
	ORAB	CA	2	2	DA	3	2	EA	5	2	FA	4	3				B + M → B	●	●	↕	↕	R	●
Push Data	PSHA													36	4	1	A → M_{SP}, SP − 1 → SP	●	●	●	●	●	●
	PSHB													37	4	1	B → M_{SP}, SP − 1 → SP	●	●	●	●	●	●
Pull Data	PULA													32	4	1	SP + 1 → SP, M_{SP} → A	●	●	●	●	●	●
	PULB													33	4	1	SP + 1 → SP, M_{SP} → B	●	●	●	●	●	●
Rotate Left	ROL							69	7	2	79	6	3				M (C ← b7 ← b0)	●	●	↕	↕	⑥	↕
	ROLA													49	2	1	A	●	●	↕	↕	⑥	↕
	ROLB													59	2	1	B	●	●	↕	↕	⑥	↕
Rotate Right	ROR							66	7	2	76	6	3				M (C → b7 → b0)	●	●	↕	↕	⑥	↕
	RORA													46	2	1	A	●	●	↕	↕	⑥	↕
	RORB													56		1	B	●	●	↕	↕	⑥	↕
Shift Left, Arithmetic	ASL							68	7	2	78	6	3				M (C ← b7 ← b0 ← 0)	●	●	↕	↕	⑥	↕
	ASLA													48	2	1	A	●	●	↕	↕	⑥	↕
	ASLB													58	2	1	B	●	●	↕	↕	⑥	↕
Shift Right, Arithmetic	ASR							67	7	2	77	6	3				M (b7 → b0 → C)	●	●	↕	↕	⑥	↕
	ASRA													47	2	1	A	●	●	↕	↕	⑥	↕
	ASRB													57	2	1	B	●	●	↕	↕	⑥	↕
Shift Right, Logic	LSR							64	7	2	74	6	3				M (0 → b7 → b0 → C)	●	●	R	↕	⑥	↕
	LSRA													44	2	1	A	●	●	R	↕	⑥	↕
	LSRB													54	2		B	●	●	R	↕	⑥	↕
Store Acmltr	STAA				97	4	2	A7	6	2	B7	5	3				A → M	●	●	↕	↕	R	●
	STAB				D7	4	2	E7	6	2	F7	5	3				B → M	●	●	↕	↕	R	●
Subtract	SUBA	80	2	2	90	3	2	A0	5	2	B0	4	3				A − M → A	●	●	↕	↕	↕	↕
	SUBB	C0	2	2	D0	3	2	E0	5	2	F0	4	3				B − M → B	●	●	↕	↕	↕	↕
Subtract Acmltrs	SBA													10	2	1	A − B → A	●	●	↕	↕	↕	↕
Subtr. with Carry	SBCA	82	2	2	92	3	2	A2	5	2	B2	4	3				A − M − C → A	●	●	↕	↕	↕	↕
	SBCB	C2	2	2	D2	3	2	E2	5	2	F2	4	3				B − M − C → B	●	●	↕	↕	↕	↕
Transfer Acmltrs	TAB													16	2	1	A → B	●	●	↕	↕	R	●
	TBA													17	2	1	B → A	●	●	↕	↕	R	●
Test, Zero or Minus	TST							60	7	2	70	6	3				M − 00	●	●	↕	↕	R	R
	TSTA													40	2	1	A − 00	●	●	↕	↕	R	R
	TSTB													50	2	1	B − 00	●	●	↕	↕	R	R

LEGEND

- OP Operation Code (Hexadecimal)
- ~ Number of MPU Cycles
- \# Number of Program Bytes
- \+ Arithmetic Plus
- − Arithmetic Minus
- · Boolean AND
- M_{SP} Contents of memory location pointed to be Stack Pointer
- \+ Boolean Inclusive OR
- ⊕ Boolean Exclusive OR
- $\bar{M}$ Complement of M
- → Transfer Into
- 0 Bit = Zero
- 00 Byte = Zero

Note – Accumulator addressing mode instructions are included in the column for IMPLIED addressing

CONDITION CODE SYMBOLS

- H Half-carry from bit 3
- I Interrupt mask
- N Negative (sign bit)
- Z Zero (byte)
- V Overflow, 2's complement
- C Carry from bit 7
- R Reset Always
- S Set Always
- ↕ Test and set if true, cleared otherwise
- ● Not Affected

AD-A081 925 ROCKWELL INTERNATIONAL COLUMBUS OH NORTH AMERICAN AI--ETC F/G 1/4
FLIGHT VERIFICATION OF DIRECT DIGITAL DRIVE FOR AN ADVANCED FLI--ETC(U)
NOV 79 L K KOHNHORST, D A MAGNACCA N62269-76-C-0201
UNCLASSIFIED NR79H-97 NADC-78207-60 NL

2 OF 2
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Table A-III Index Register and Stack Manipulation Instructions (MC 6800)

POINTER OPERATIONS	MNEMONIC	IMMED OP	IMMED ~	IMMED ≈	DIRECT OP	DIRECT ~	DIRECT ≈	INDEX OP	INDEX ~	INDEX ≈	EXTND OP	EXTND ~	EXTND ≈	IMPLIED OP	IMPLIED ~	IMPLIED ≈	BOOLEAN/ARITHMETIC OPERATION	COND. CODE REG. 5 H	4 I	3 N	2 Z	1 V	0 C
Compare Index Reg	CPX	8C	3	3	9C	4	2	AC	6	2	BC	5	3				$X_H - M, X_L - (M+1)$	●	●	7	↕	8	●
Decrement Index Reg	DEX													09	4	1	$X - 1 \rightarrow X$	●	●	●	↕	●	●
Decrement Stack Pntr	DES													34	4	1	$SP - 1 \rightarrow SP$	●	●	●	●	●	●
Increment Index Reg	INX													08	4	1	$X + 1 \rightarrow X$	●	●	●	↕	●	●
Increment Stack Pntr	INS													31	4	1	$SP + 1 \rightarrow SP$	●	●	●	●	●	●
Load Index Reg	LDX	CE	3	3	DE	4	2	EE	6	2	FE	5	3				$M \rightarrow X_H, (M+1) \rightarrow X_L$	●	●	9	↕	R	●
Load Stack Pntr	LDS	8E	3	3	9E	4	2	AE	6	2	BE	5	3				$M \rightarrow SP_H, (M+1) \rightarrow SP_L$	●	●	9	↕	R	●
Store Index Reg	STX				DF	5	2	EF	7	2	FF	6	3				$X_H \rightarrow M, X_L \rightarrow (M+1)$	●	●	9	↕	R	●
Store Stack Pntr	STS				9F	5	2	AF	7	2	BF	6	3				$SP_H \rightarrow M, SP_L \rightarrow (M+1)$	●	●	9	↕	R	●
Indx Reg → Stack Pntr	TXS													35	4	1	$X - 1 \rightarrow SP$	●	●	●	●	●	●
Stack Pntr → Indx Reg	TSX													30	4	1	$SP + 1 \rightarrow X$	●	●	●	●	●	●

Table A-IV Jump and Branch Instructions (MC 6800)

OPERATIONS	MNEMONIC	RELATIVE OP	RELATIVE ~	RELATIVE #	INDEX OP	INDEX ~	INDEX #	EXTND OP	EXTND ~	EXTND #	IMPLIED OP	IMPLIED ~	IMPLIED #	BRANCH TEST	COND. CODE REG. 5 H	4 I	3 N	2 Z	1 V	0 C
Branch Always	BRA	20	4	2										None	●	●	●	●	●	●
Branch If Carry Clear	BCC	24	4	2										C = 0	●	●	●	●	●	●
Branch If Carry Set	BCS	25	4	2										C = 1	●	●	●	●	●	●
Branch If = Zero	BEQ	27	4	2										Z = 1	●	●	●	●	●	●
Branch If ≥ Zero	BGE	2C	4	2										$N \oplus V = 0$	●	●	●	●	●	●
Branch If > Zero	BGT	2E	4	2										$Z + (N \oplus V) = 0$	●	●	●	●	●	●
Branch If Higher	BHI	22	4	2										C + Z = 0	●	●	●	●	●	●
Branch If ≤ Zero	BLE	2F	4	2										$Z + (N \oplus V) = 1$	●	●	●	●	●	●
Branch If Lower Or Same	BLS	23	4	2										C + Z = 1	●	●	●	●	●	●
Branch If < Zero	BLT	2D	4	2										$N \oplus V = 1$	●	●	●	●	●	●
Branch If Minus	BMI	2B	4	2										N = 1	●	●	●	●	●	●
Branch If Not Equal Zero	BNE	26	4	2										Z = 0	●	●	●	●	●	●
Branch If Overflow Clear	BVC	28	4	2										V = 0	●	●	●	●	●	●
Branch If Overflow Set	BVS	29	4	2										V = 1	●	●	●	●	●	●
Branch If Plus	BPL	2A	4	2										N = 0	●	●	●	●	●	●
Branch To Subroutine	BSR	8D	8	2										See Special Operations	●	●	●	●	●	●
Jump	JMP				6E	4	2	7E	3	3					●	●	●	●	●	●
Jump To Subroutine	JSR				AD	8	2	BD	9	3					●	●	●	●	●	●
No Operation	NOP										01	2	1	Advances Prog. Cntr. Only	●	●	●	●	●	●
Return From Interrupt	RTI										3B	10	1		10					
Return From Subroutine	RTS										39	5	1	See Special Operations	●	●	●	●	●	●
Software Interrupt	SWI										3F	12	1		●	●	●	●	●	●
Wait for Interrupt*	WAI										3E	9	1		●	11	●	●	●	●

*WAI puts Address Bus, R/W, and Data Bus in the three state mode while VMA is held low.

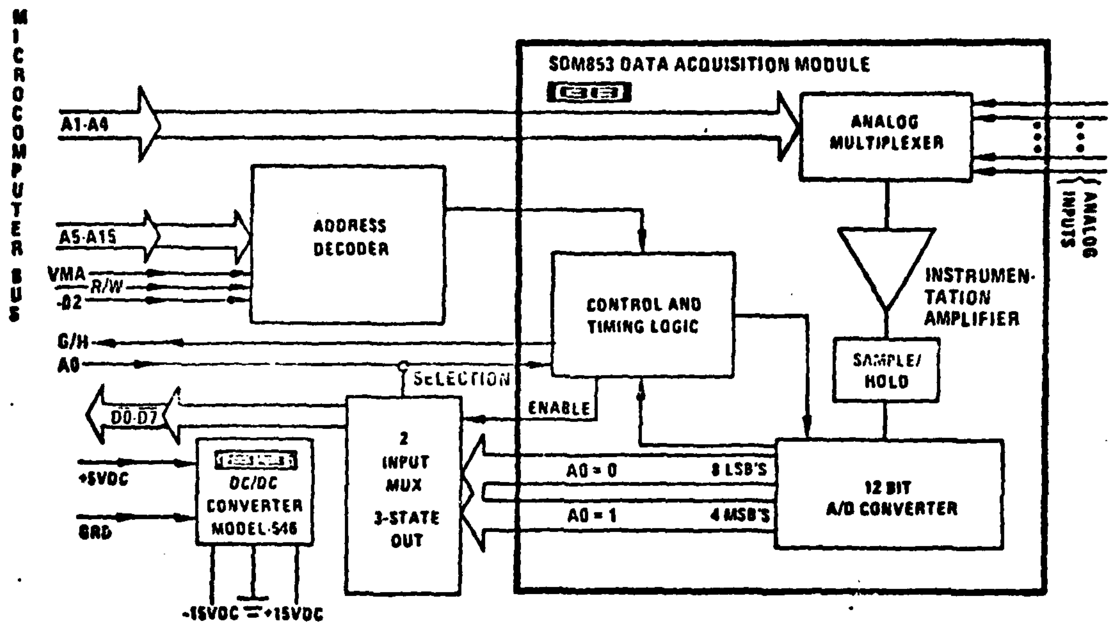

Figure A-4 Analog to Digital Converter - MP7208/7216

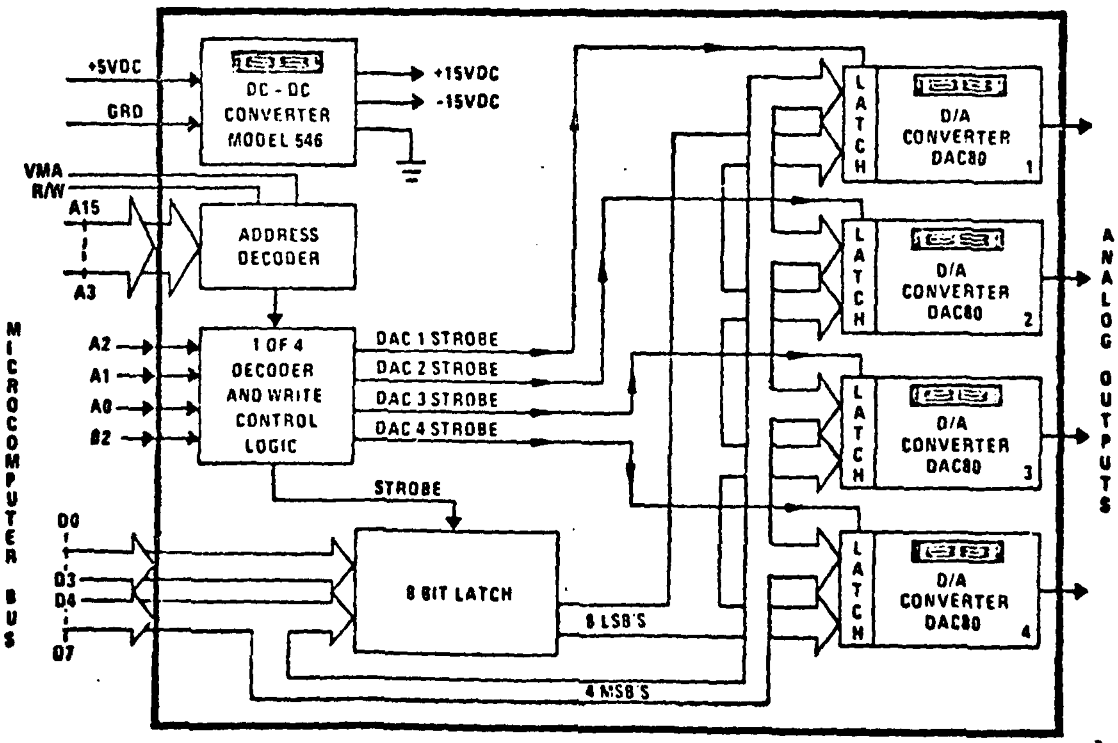

Figure A-5 Digital To Analog Converter - MP7104

TABLE A-V

CONVERTER CHARACTERISTICS ANALOG TO DIGITAL

NUMBER OF CHANNELS	8
INPUT VOLTAGE	± 10 MV TO ± 10 V
INPUT IMPEDANCE	100 MEGOHMS
RESOLUTION	12 Bits BINARY
CONVERSION TIME (± 10 V)	33 MICROSECONDS

DIGITAL TO ANALOG

NUMBER OF CHANNELS	4
OUTPUT VOLTAGE, VDC	±2.5, ±5, ±10, 0 TO 5, 0 TO 10
OUTPUT IMPEDANCE	1 OHM
RESOLUTION	12 Bits BINARY

APPENDIX B

DIGITAL FLY-BY-WIRE AFCAS

FLIGHT PROGRAM SOFTWARE

PROGRAM - DIGITAL FBW SUBROUTINE - TEMP STORAGE DATE 04-04-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
00 50		XX XX		CMD1
00 52		XX XX		POS1
00 54		XX XX		CMD2
00 56		XX XX		POS2
00 58		XX XX		ERROR
00 5A		XX --		CARRY
00 5C				
00 5E		XX --		MONITOR CONTROL
00 60		XX --		CMD CTR
00 62		XX --		POS CTR
00 64		XX XX		ERROR CTR
00 66		XX YY		XX, PLUS ON TIME; YY, MINUS ON TIME

PROGRAM - DIGITAL FBW SUBROUTINE - INITIALIZE DATE 04-04-79

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CC 6A	CE	04 00		LDX	+5VDC
CC 6D	FF	EF 06		STX	TURN ON DAC-4
CC 70	OF	-- --		SEI	SET INTERRUPT MASK
CC 71	86	1F --		LDA	10
CC 73	97	60 --		STA	CMD CTR
CC 75	97	62 --		STA	POS CTR
CC 77	CE	04 00		LDX	1 SEC
CC 7A	DF	64 --		STA	ERROR CTR
CC 7C	20	02 --		BRA	TO PROG START

PROGRAM - DIGITAL FBW | SUBROUTINE - INPUT 1 | DATE 02-28-79

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CC 80	CE	07 FF	3/ 3	LDX	+10VDC
CC 83	FF	EF 00	6/ 9	STX	DAC-1
CC 86	FF	EF 02	6/ 15	STX	DAC-2
CC 89	B6	EC 00	4/ 19	LDA-A	START A-D CH. 0 CMD
CC 8C	01	-- --	*2/ 54	NOP	WAIT FOR CONVERSION
CC 8D	FE	EC 00	5/ 59	LDX	CMD IN "X"
CC 90	DF	50 --	5/ 64	STX	
CC 92	B6	EC 04	4/ 68	LDA-A	START A-D CH. 2 POS.
CC 95	01	-- --	*2/ 105	NOP	WAIT FOR CONVERSION
CC 96	FE	EC 04	5/ 110	LDX	POS IN "X"
CC 99	DF	52 --	5/ 115	STX	

* 33 μsec for A/D Conversion

PROGRAM - DIGITAL FBW | SUBROUTINE - CMD1 LIMITS | DATE 03-28-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CC 9B	96	50 --	3/ 118	LDA-A CMD-1
CC 9D	2B	0B --	4/ 122	BMI TO AA
CC 9F	81	04 --	2/ 124	CMP
CC A1	2B	13 --	4/ 128	BMI TO B6
CC A3	CE	04 00	3/ 131	LDX +5V
CC A6	DF	50 --	5/ 136	STX CMD1
CC A8	20	12 --	4/ 140	BRA TO BC
CC AA	40	-- --	2/ 124	NEG
CC AB	81	05 --	2/ 126	CMP
CC AD	2B	07 --	4/ 130	BMI TO B6
CC AF	CE	FC 00	3/ 133	LDX -5V
CC B2	DF	50 --	5/ 138	STX CMD1
CC B4	20	06 --	4/ 142	BRA TO BC
CC B6	73	00 00	6/ 134	COM
CC B9	73	00 00	6/ 140	COM
CC BC	73	00 00	6/ 148	COM
CC BF	20	3F --	4/ 152	BRA

PROGRAM - DIGITAL FBW SUBROUTINE - ERROR DATE 02-28-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 00	96	53 --	3/ 3	LDA-A POSITION (L.S. BYTE)
CD 02	43	-- --	2/ 5	COM-A
CD 03	9B	51 --	3/ 8	ADD LS = CMD - POS
CD 05	24	04 --	4/ 12	BCC
CD 07	C6	01	2/ 14	LDA-B 01
CD 09	20	03 --	4/ 18	BRA
CD 0B	01	-- --	2/ 14	NOP
CD 0C	01	-- --	2/ 16	NOP
CD 0D	5F	-- --	2/ 18	CLR-B
CD 0E	D7	5A --	4/ 22	STA-B SAVE CARRY
CD 10	D6	52 --	3/ 25	LDA-B POSITION (M.S. BYTE)
CD 12	53	-- --	2/ 27	COM-B
CD 13	DB	50 --	3/ 30	ADD-B
CD 15	DB	5A --	3/ 33	ADD-B = CMD - POS
CD 17	57	-- --	2/ 35	ASR-B
CD 18	46	-- --	2/ 37	ROR-A
CD 19	57	-- --	2/ 39	ASR-B
CD 1A	46	-- --	2/ 41	ROR-A
CD 1B	D7	58 --	4/ 45	STA-B ERROR (HI)
CD 1D	97	59 --	4/ 49	STA-A ERROR (LO)
CD 1F	01	-- --	2/ 51	NOP

PROGRAM - DIGITAL FBW SUBROUTINE - GAIN CONTROL DATE 03-28-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 20	D6	59 --	3/ 48	LDA-B ERROR, LO
CD 22	96	58 --	3/ 51	LDA-A ERROR, HI
CD 24	01	-- --	2/ 53	NOP
CD 25	01	-- --	2/ 55	NOP
CD 26	4D	-- --	2/ 57	TST-A
CD 27	2B	21 --	4/ 61	BMI TO NEG ERROR

PROGRAM - DIGITAL FBW   SUBROUTINE - POSITIVE ERROR   DATE 04-10-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 29	84	07 --	2/ 63	AND-A
CD 2B	26	OF --	4/ 67	BNE TO SET MAX MODULATION TIME
CD 2D	C4	80 --	2/ 69	AND-B
CD 2F	26	OE --	4/ 73	BNE TO SET MAX MOD. TIME
CD 31	D6	59 --	3/ 76	LDA-B ERROR, LO
CD 33	D7	66 --	4/ 80	STA-B TIME FOR POS. MOD.
CD 35	86	7F --	2/ 82	LDA-A 7F
CD 37	10	-- --	2/ 84	SBA
CD 38	97	67 --	4/ 88	STA-A TIME FOR NEG. MOD.
CD 3A	20	34 --	4/ 92	BRA TO POS. OUTPUT
CD 3C	01	01 01	6/ 73	NOP
CD 3F	86	7F --	2/ 75	LDA-A 7F
CD 41	97	66 --	4/ 79	STA-A TIME FOR POS. MOD.
CD 43	C6	00 --	2/ 81	LDA-B 00
CD 45	D7	67 --	4/ 85	STA-B TIME FOR NEG. MOD.
CD 47	01	-- --	2/ 87	NOP
CD 48	20	26 --	4/ 91	BRA TO POS. OUTPUT

PROGRAM - DIGITAL FBW SUBROUTINE - NEGATIVE ERROR DATE 04-10-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 4A	43	-- --	2/ 63	COM-A
CD 4B	84	07 --	2/ 65	AND
CD 4D	26	11 --	4/ 69	BNE TO SET MAX NEG. MOD. TIME
CD 4F	53	-- --	2/ 71	COM-B
CD 50	C4	80 --	2/ 73	AND
CD 52	26	10 --	4/ 77	BNE TO SET MAX NEG. MOD. TIME
CD 54	D6	59 --	3/ 80	LDA-B ERROR, LO
CD 56	53	-- --	2/ 82	COM-B
CD 57	D7	67 --	4/ 86	STA-B TIME FOR NEG. MOD. TIME
CD 59	86	7F --	2/ 88	LDA-A 7F
CD 5B	10	-- --	2/ 90	SBA
CD 5C	97	66 --	4/ 94	STA-A TIME FOR POS. MOD. TIME
CD 5E	20	30 --	4/ 98	BRA TO NEG. OUTPUT
CD 60	01	01 --	4/ 73	NOP
CD 62	01	01 --	4/ 77	NOP
CD 64	86	7F --	2/ 79	LDA-A 7F
CD 66	97	67 --	4/ 83	STA-A TIME FOR NEG. MOD.
CD 68	C6	00 --	2/ 85	LDA-B 00
CD 6A	D7	66 --	4/ 89	STA-B TIME FOR POS. MOD.
CD 6C	01	01 --	4/ 93	NOP
CD 6E	20	20 --	4/ 97	BRA TO NEG. OUTPUT

PROGRAM - DIGITAL FBW SUBROUTINE - PLUS OUTPUT DATE 04-04-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 70	86	7F --	2/ 2	LDA-A
CD 72	4A	-- --	2/ 4	DEC-A
CD 73	2A	FD --	4/ 774	BPL
CD 75	96	66 --	2/ 776	LDA-A PLUS ON TIME
CD 77	4A	-- --	2/	DEC-A
CD 78	2A	FD --	4/ 782*	BPL
CD 7A	CE	F8 00	3/ 785	LDX -10V
CD 7D	FF	EF 00	6/ 791	STX DAC-1
CD 80	FF	EF 02	6/ 797	STX DAC-2
CD 83	96	67 --	2/ 799	LDA-A MINUS ON TIME
CD 85	4A	-- --	2/	DEC-A
CD 86	2A	FD --	4/1567*	BPL
CD 88	20	26 --	4/1571	BRA TO MONITOR

*TIME WITH ZERO ERROR

PROGRAM - DIGITAL FBW   SUBROUTINE - MINUS OUTPUT   DATE 04-04-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 90	96	66 --	2/ 2	LDA-A TIME FOR PLUS OUTPUT
CD 92	D6	67 --	2/ 4	LDA-B TIME FOR MINUS OUTPUT
CD 94	4A	-- --	2/	DEC-A
CD 95	2A	FD --	4/ 774*	BPL
CD 97	CE	F8 00	3/ 777	LDX -10V
CD 9A	FF	EF 00	6/ 783	STX DAC-1
CD 9D	FF	EF 02	6/ 789	STX DAC-2
CD A0	5A	-- --	2/	DEC-B
CD A1	2A	FD --	4/ 795*	BPL
CD A3	86	7F --	2/ 797	LDA-A
CD A5	4A	-- --	2/	DEC-A
CD A6	2A	FD --	4/1566*	BPL
CD A8	20	06 --	4/1570	BRA TO MONITOR
				*TIME WITH ZERO ERROR

PROGRAM - DIGITAL FBW   SUBROUTINE - INPUT 2   DATE 04-02-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD B0	B6	EC 02	4/ 4	LDA-A START A-D CH. 1 CMD-2
CD B3	01	-- --	*2/ 37	NOP
CD B4	FE	EC 02	5/ 42	LDX CMD-2
CD B7	DF	54 --	5/ 47	STX
CD B9	B6	EC 06	4/ 51	LDA-A START A-D CH. 3 POS-2
CD BC	01	-- --	*2/ 86	NOP
CD BD	FE	EC 06	5/ 91	LDX POS-2
CD C0	DF	56 --	5/ 96	STX
CD C2	96	54 --	3/ 99	LDA-A CMD-2
CD C4	2B	0B --	4/ 103	BMI TO TEST NEG. LIMITS
CD C6	81	04 --	2/ 105	CMP TEST POS. LIMITS
CD C8	2B	13 --	4/ 109	BMI
CD CA	CE	04 00	3/ 112	LDX +5V
CD CD	DF	54 --	4/ 117	STX CMD-2
CD CF	20	12 --	4/ 121	BRA TO EXIT
CD D1	40	-- --	2/ 105	NEG TEST NEG. LIMITS
CD D2	81	05 --	2/ 107	CMP
CD D4	2B	07 --	4/ 111	BMI
CD D6	CE	FC 00	3/ 114	LDX -5V
CD D9	DF	54 --	5/ 119	STX CMD-2
CD DB	20	06 --	4/ 123	BRA
CD DD	73	00 00	6/ 117	COM
CD E0	73	00 00	6/ 123	COM
CD E3	73	00 00	6/ 129	COM
CD E6	96	5E --	3/ 132	LDA-A MONITOR CONTROL
CD E8	2A	16 --	4/ 136	BPL TO CMD MONITOR
CD EA	20	54 --	4/ 140	BRA TO POS. MONITOR

PROGRAM - DIGITAL FBW SUBROUTINE - CMD MONITOR DATE 04-02-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CE 00	96	51 --	3/ 3	LDA-A CMD1 (LO)
CE 02	43	-- --	2/ 5	COM-A
CE 03	9B	55 --	3/ 8	ADD CMD2 (LO)
CE 05	24	04 --	4/ 12	BCC
CE 07	C6	01 --	2/ 14	LDA-B 01
CE 09	20	03 --	4/ 18	BRA
CE 0B	01	01 --	4/ 16	NOP
CE 0D	5F	-- --	2/ 18	CLR-B
CE 0E	D7	5A --	4/ 22	STA-B SAVE CARRY
CE 10	D6	50 --	3/ 25	LDA-B CMD1 (HI)
CE 12	53	-- --	2/ 27	COM-B
CE 13	DB	54 --	3/ 30	ADD-B CMD2 (HI)
CE 15	DB	5A --	3/ 33	ADD-B CARRY
CE 17	2A	01 --	4/ 37	BPL
CE 19	53	-- --	2/ 39	COM-B
CE 1A	C4	07 --	2/ 41	AND-B
CE 1C	26	06 --	4/ 45	BNE TO DEC CMD CTR
CE 1E	86	1F --	2/ 47	LDA-A
CE 20	97	60 --	4/ 51	STA-A RESET CMD CTR
CE 22	20	07 --	4/ 55	BRA TO ERROR MONITOR
CE 24	7A	00 60	6/ 51	DEC CMD CTR
CE 27	2A	02 --	4/ 55	BPL TO ERROR MONITOR
CE 29	20	76 --	4/	BRA TO TURN OFF RELAY
CE 2B	86	80 --	2/ 57	LDA-A -1
CE 2D	97	5E --	4/ 61	STA-A MONITOR CONTROL
CE 2F	20	4F --	4/ 65	BRA TO ERROR MONITOR

PROGRAM - DIGITAL FBW SUBROUTINE - POS MONITOR DATE 04-02-79

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CE 40	96	53 --	3/ 3	LDA-A POS1 (LO)
CE 42	43	-- --	2/ 5	COM-A
CE 43	9B	57 --	3/ 8	ADD POS2 (LO)
CE 45	24	04 --	4/ 12	BCC
CE 47	C6	01 --	2/ 14	LDA-B 01
CE 49	20	03 --	4/ 18	BRA
CE 4B	01	01 --	4/ 16	NOP
CE 4D	5F	-- --	2/ 18	CLR-B
CE 4E	D7	5A --	4/ 22	STA-B SAVE CARRY
CE 50	D6	52 --	3/ 25	LDA-B POS1 (HI)
CE 52	53	-- --	2/ 27	COM-B
CE 53	DB	56 --	3/ 30	ADD-B POS2 (HI)
CE 55	DB	5A --	3/ 33	ADD-B CARRY
CE 57	2A	01 --	4/ 37	BPL
CE 59	53	-- --	2/ 39	COM-B.
CE 5A	C4	07	2/ 41	AND-B
CE 5C	26	06 --	4/ 45	BNE TO DEC POS CTR
CE 5E	86	1F --	2/ 47	LDA-A
CE 60	97	62 --	4/ 51	STA-A RESET POS CTR
CE 62	20	07 --	4/ 55	BRA TO ERROR MONITOR
CE 64	7A	00 62	6/ 51	DEC POS CTR
CE 67	2A	02 --	4/ 55	BPL TO ERROR MONITOR
CE 69	20	36 --	4/	BRA TO TURN OFF RELAY
CE 6B	86	08 --	2/ 57	LDA-A +08
CE 6D	97	5E --	4/ 61	STA-A MONITOR CONTROL
CE 6F	20	0F --	4/ 65	BRA TO ERROR MONITOR

PROGRAM - DIGITAL FBW SUBROUTINE - MONITOR ERROR DATE 04-02-79

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CE 80	96	58 --	3/ 3	LDA-A	ERROR (HI)
CE 82	2A	04 --	4/ 7	BPL	
CE 84	96	67 --	3/ 10	LDA-A	TIME FOR MINUS ON
CE 86	20	04 --	4/ 14	BRA	TO AND
CE 88	96	66 --	3/ 10	LDA-A	TIME FOR PLUS ON
CE 8A	01	01 --	4/ 14	NOP	
CE 8C	84	40 --	2/ 16	AND	
CE 8E	27	09 --	4/ 20	BEQ	TO RESET COUNTER
CE 90	DE	64 --	3/ 23	LDX	ERROR COUNTER
CE 92	09	-- --	4/ 27	DEX	
CE 93	DF	64 --	4/ 32	STX	
CE 95	26	07 --	4/ 36	BNE	TO PROG START
CE 97	20	08 --	4/ 40	BRA	TO TURN OFF RELAY
CE 99	CE	04 00	3/ 43	LDX	1 SECOND
CE 9C	DF	64 --	5/ 48	STX	
CE 9E	7E	CC 80	3/ 51	JMP	TO PROG START
CE A1	CE	00 00	3/	LDX	OV
CE A4	FF	EF 06		STX	TURN OFF RELAY
CE A7	86	04 --		LDA	4
CE A9	CE	7F FF		LDX	.25 SEC
CE AC	09	-- --		DEX	
CE AD	26	FD --		BNE-3	
CE AF	4A	-- --		DEC A	
CE B0	26	F7 --		BNE-9	TO CEA9
CE B2	7E	CC 6A		JMP	TO START

PROM MAP

P SHWP	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0000	~~96~~	~~3F~~	~~EB~~	~~EB~~	~~37~~	~~36~~	~~FC~~	~~EB~~	~~36~~	~~26~~	~~EB~~	~~FB~~	~~26~~	~~06~~	~~FB~~	~~EB~~
0010	~~07~~	~~B7~~	~~EB~~	~~EC~~	~~36~~	~~17~~	~~EB~~	~~EB~~	~~36~~	~~36~~	~~EB~~	~~EB~~	~~26~~	~~26~~	~~EB~~	~~FB~~
0020	~~17~~	~~37~~	~~EC~~	~~EC~~	~~26~~	~~26~~	~~EB~~	~~FB~~	~~37~~	~~37~~	~~EB~~	~~EB~~	~~36~~	~~27~~	~~EB~~	~~FB~~
0030	~~27~~	~~17~~	~~EC~~	~~EB~~	~~07~~	~~36~~	~~EB~~	~~EC~~	~~36~~	~~16~~	~~EB~~	~~EB~~	~~07~~	~~26~~	~~EB~~	~~FB~~
0040	~~D9~~	~~D8~~	~~12~~	~~12~~	~~F9~~	~~D8~~	~~12~~	~~12~~	~~C9~~	~~C9~~	~~02~~	~~12~~	~~D9~~	~~D9~~	~~12~~	~~12~~
0050	~~C8~~	~~E9~~	~~12~~	~~13~~	~~C9~~	~~D8~~	~~13~~	~~12~~	~~E9~~	~~C9~~	~~02~~	~~12~~	~~CC~~	~~FB~~	~~12~~	~~12~~
0060	~~E8~~	~~F9~~	~~12~~	~~12~~	~~D9~~	~~C9~~	~~13~~	~~02~~	~~D8~~	~~C9~~	CE	04	00	FF	EF	06
0070	0F	86	1F	97	60	97	62	CE	04	00	DF	64	20	02	~~02~~	~~12~~
0080	CE	07	FF	FF	EF	00	FF	EF	02	D6	EC	00	01	FE	EC	00
0090	DF	50	B6	EC	04	01	FE	EC	04	DF	52	96	50	2B	0B	81
00A0	04	2B	13	CE	04	00	DF	50	20	12	40	81	05	2B	07	CE
00B0	FC	00	DF	50	20	06	73	00	00	73	00	00	73	00	00	20
00C0	3F	~~D9~~	~~12~~	~~12~~	~~D9~~	~~C8~~	~~12~~	~~12~~	~~D9~~	~~D8~~	~~16~~	~~12~~	~~C9~~	~~D9~~	~~12~~	~~12~~
00D0	~~C8~~	~~D8~~	~~12~~	~~12~~	~~D9~~	~~C9~~	~~12~~	~~12~~	~~C8~~	~~F9~~	~~12~~	~~12~~	~~D9~~	~~D9~~	~~12~~	~~12~~
00E0	~~C9~~	~~D9~~	~~12~~	~~12~~	~~D1~~	~~D9~~	~~02~~	~~02~~	~~D9~~	~~D8~~	~~12~~	~~12~~	~~D9~~	~~D8~~	~~12~~	~~12~~
00F0	~~D8~~	~~E9~~	~~12~~	~~12~~	~~D8~~	~~D8~~	~~12~~	~~03~~	~~D9~~	~~D9~~	~~12~~	~~12~~	~~C9~~	~~F8~~	~~12~~	~~02~~
0100	96	53	43	9B	51	24	04	C6	01	20	03	01	01	5F	D7	5A
0110	D6	52	53	DB	50	DB	5A	57	46	57	46	D7	58	97	59	01
0120	D6	59	96	58	01	01	4D	2B	21	84	07	26	0F	C4	80	26
0130	0E	D6	59	D7	66	86	7F	10	97	67	20	34	01	01	01	86
0140	7F	97	66	C6	00	D7	67	01	20	26	43	84	07	26	11	53
0150	C4	80	26	10	D6	59	53	D7	67	86	7F	10	97	66	20	30
0160	01	01	01	01	86	7F	97	67	C6	00	D7	66	01	01	20	20
0170	86	7F	4A	2A	FD	96	66	4A	2A	FD	CE	F8	00	FF	EF	00
0180	FF	EF	02	96	67	4A	2A	FD	20	26	~~FF~~	~~FD~~	~~D3~~	~~D3~~	~~FF~~	~~FF~~
0190	96	66	D6	67	4A	2A	FD	CE	F8	00	FF	EF	00	FF	EF	02
01A0	5A	2A	FD	86	7F	4A	2A	FD	20	06	~~FB~~	~~FF~~	~~33~~	~~33~~	~~FF~~	~~FF~~
01B0	B6	EC	02	01	FE	EC	02	DF	54	B6	EC	06	01	FE	EC	06
01C0	DF	56	96	54	2B	0B	81	04	2B	13	CE	04	00	DF	54	20
01D0	12	40	81	05	2B	07	CE	FC	00	DF	54	20	06	73	00	00
01E0	73	00	00	73	00	00	96	5E	2A	16	20	54	~~6C~~	~~6D~~	~~00~~	~~00~~
01F0	2C	2C	10	18	4C	2C	00	00	4C	4C	02	00	6C	2D	00	00
0200	96	51	43	9B	55	24	04	C6	01	20	03	01	01	5F	D7	5A
0210	D6	50	53	DB	54	DB	5A	2A	01	53	C4	07	26	06	86	1F
0220	97	60	20	07	7A	00	60	2A	02	20	76	86	80	97	5E	20
0230	4F	~~06~~	~~EB~~	~~EB~~	~~26~~	~~1F~~	~~EB~~	~~EB~~	~~36~~	~~26~~	~~EB~~	~~EB~~	~~06~~	~~26~~	~~EB~~	~~EB~~
0240	96	53	43	9B	57	24	04	C6	01	20	03	01	01	5F	D7	5A
0250	D6	52	53	DB	56	DB	5A	2A	01	53	C4	07	26	06	86	1F
0260	97	62	20	07	7A	00	62	2A	02	20	36	86	08	97	5E	20
0270	0F	~~F8~~	~~12~~	~~12~~	~~D9~~	~~C9~~	~~12~~	~~12~~	~~C9~~	~~D8~~	~~12~~	~~10~~	~~D9~~	~~C9~~	~~12~~	~~02~~
0280	96	58	2A	04	96	67	20	04	96	66	01	01	84	40	27	09
0290	DE	64	09	DF	64	26	07	20	08	CE	04	00	DF	64	7E	CC
02A0	80	CE	00	00	FF	EF	06	86	04	CE	7F	FF	09	26	FD	4A
02B0	26	F7	7E	CC	6A	~~36~~	~~EC~~	~~EB~~	~~26~~	~~27~~	~~EB~~	~~EB~~	~~36~~	~~06~~	~~FB~~	~~EB~~
02C0	~~D8~~	~~C9~~	~~12~~	~~92~~	~~C8~~	~~C9~~	~~12~~	~~12~~	~~D9~~	~~E9~~	~~02~~	~~02~~	~~E9~~	~~E8~~	~~10~~	~~02~~
02D0	~~C8~~	~~E9~~	~~12~~	~~12~~	~~C9~~	~~C9~~	~~12~~	~~02~~	~~E9~~	~~D8~~	~~12~~	~~12~~	~~E9~~	~~D9~~	~~12~~	~~12~~
02E0	~~C8~~	~~C8~~	~~11~~	~~12~~	~~D9~~	~~89~~	~~12~~	~~12~~	~~E9~~	~~E9~~	~~12~~	~~12~~	~~D9~~	~~D9~~	~~32~~	~~12~~
02F0	~~C8~~	~~F8~~	~~12~~	~~13~~	~~C8~~	~~C9~~	~~12~~	~~12~~	~~D9~~	~~D9~~	~~12~~	~~12~~	~~C8~~	~~F9~~	~~12~~	~~12~~
0300	~~B7~~	~~B7~~	~~FB~~	~~FB~~	~~F7~~	~~77~~	~~FB~~	~~FB~~	~~13~~	~~57~~	~~FB~~	~~FB~~	~~32~~	~~97~~	~~FF~~	~~FB~~
0310	~~77~~	~~93~~	~~EB~~	~~FF~~	~~93~~	~~F7~~	~~FF~~	~~F9~~	~~93~~	~~F3~~	~~FB~~	~~FF~~	~~83~~	~~93~~	~~FB~~	~~FF~~
0320	~~B3~~	~~B3~~	~~FF~~	~~FF~~	~~B3~~	~~B7~~	~~FB~~	~~FB~~	~~53~~	~~B3~~	~~FF~~	~~FB~~	~~B3~~	~~93~~	~~FF~~	~~FF~~
0330	~~B7~~	~~97~~	~~FF~~	~~FF~~	~~92~~	~~B3~~	~~FF~~	~~BB~~	~~33~~	~~92~~	~~FF~~	~~FB~~	~~92~~	~~63~~	~~FF~~	~~FB~~
0340	~~0C~~	~~08~~	~~02~~	~~10~~	~~2C~~	~~68~~	~~10~~	~~20~~	~~6C~~	~~2C~~	~~00~~	~~02~~	~~4C~~	~~2C~~	~~00~~	~~00~~
0350	~~2C~~	~~0C~~	~~02~~	~~02~~	~~AC~~	~~28~~	~~00~~	~~0A~~	~~0C~~	~~2C~~	~~02~~	~~00~~	~~6C~~	~~2B~~	~~00~~	~~00~~
0360	~~28~~	~~28~~	~~00~~	~~02~~	~~0C~~	~~EC~~	~~04~~	~~0A~~	~~6C~~	~~4C~~	~~00~~	~~00~~	~~6A~~	~~7C~~	~~00~~	~~10~~
0370	~~6C~~	~~6C~~	~~04~~	~~08~~	~~0C~~	~~0C~~	~~10~~	~~00~~	~~EB~~	~~6C~~	~~00~~	~~00~~	~~4B~~	~~EC~~	~~10~~	~~12~~
0380	~~F3~~	~~B7~~	~~FB~~	~~FB~~	~~93~~	~~B3~~	~~FF~~	~~F3~~	~~13~~	~~92~~	~~FF~~	~~FF~~	~~B3~~	~~B3~~	~~FF~~	~~FF~~
0390	~~B3~~	~~B7~~	~~FF~~	~~FB~~	~~F3~~	~~F3~~	~~FF~~	~~FB~~	~~73~~	~~F3~~	~~FF~~	~~FF~~	~~33~~	~~93~~	~~FF~~	~~FF~~
03A0	~~F7~~	~~B3~~	~~FB~~	~~FB~~	~~F2~~	~~F3~~	~~FF~~	~~EB~~	~~87~~	~~B3~~	~~FF~~	~~F7~~	~~93~~	~~F2~~	~~FF~~	~~EF~~
03B0	~~F7~~	~~B7~~	~~FF~~	~~F9~~	~~F3~~	~~73~~	~~FF~~	~~EF~~	~~F3~~	~~93~~	~~DF~~	~~FF~~	~~53~~	~~B3~~	~~EB~~	~~FF~~
03C0	~~4C~~	~~68~~	~~12~~	~~10~~	~~48~~	~~4C~~	~~00~~	~~02~~	~~6C~~	~~6C~~	~~00~~	~~00~~	~~6C~~	~~4C~~	~~02~~	~~00~~
03D0	~~28~~	~~48~~	~~00~~	~~10~~	~~6C~~	~~6C~~	~~00~~	~~00~~	~~0B~~	~~4C~~	~~00~~	~~00~~	~~4C~~	~~4C~~	~~00~~	~~00~~
03E0	~~08~~	~~08~~	~~02~~	~~00~~	~~4C~~	~~68~~	~~06~~	~~08~~	~~2C~~	~~EC~~	~~00~~	~~00~~	~~6C~~	~~5C~~	~~00~~	~~00~~
03F0	~~08~~	~~6C~~	~~10~~	~~16~~	~~0C~~	~~0B~~	~~00~~	~~00~~	~~6C~~	~~6C~~	~~10~~	~~00~~	~~6C~~	~~6B~~	CC	6A

NOTES:
1. Data lined through is not used.
2. Starting Address is loaded in locations $03FE_{16}$ & $03FF_{16}$
3. Addresses and data are hexidecimal notation.

APPENDIX C

GENERAL TEST PLAN/PROCEDURES

I. TEST PLAN AND OBJECTIVES

II. GROUND TEST PROCEDURE

III. SYSTEM DESCRIPTION AND PILOT INFORMATION

IV. FLIGHT TEST PROCEDURE

V. FLIGHT INSTRUMENTATION

VI. REFERENCES

I. TEST PLAN AND OBJECTIVES

This appendix contains the ground and flight test procedures, system description, pilot information, and flight instrumentation information. The prime objective of the flight test program is to evaluate the microcomputer controlled direct digital drive fly-by-wire characteristics of the AFCAS in a T-2C aircraft. Approximately three hours of flight testing will be accomplished at the Columbus, Ohio facility of Rockwell International.

II. GROUND TEST PROCEDURE

1. FILL AND BLEED HYDRAULIC SYSTEM

A 3000 psi ground cart containing MIL-H-83282 fluid is required.

- Before reconnecting AFCAS actuator, temporarily connect rudder actuator pressure and return lines together. Hose and adaptor fittings provided by Dept. 71.
- Attach ground cart pressure, fill, and suction lines to aircraft.
- Apply 85 psi at fill fitting.
- Bleed air from heat exchanger bleed port located at the upper left aft corner of heat exchanger.
- Bleed air at pump suction, pressure, and case drain ports.
- Disconnect ground cart.
- Reconnect pressure and return lines to rudder actuator.

2. ELECTRICAL WIRING VERIFICATION

- Continuity check all wiring per AFCAS Drawing No. 8691-546606A.
- Fit check and verify all mating connectors used on rudder actuator, position LVDT's, force transducers, EDU, microcomputer, and microcomputer power supply.

3. SYSTEM CHECKOUT

Prepare aircraft to provide hydraulic pump and system operations from external ground power.

On relay panel assembly 310-545549-11, located at F.S. 125 in the LH equipment bay

  - Remove #1 GBC Relay No. 3, P/N BR12-675A8-S73.
  - Add 20 AWG jumper wire between pins 3 and 5 of relay socket.
  - Remove #2 GBC Relay No. 3, P/N BR12-675A8-S73.
  - Add 20 AWG jumper wire between pins 3 and 5 of relay socket.

In the aft equipment bay at F.S. 270 Centerline

  - Replace Wire C237A20NT, connected between hydraulic pump motor relay (P/N MS34171D1) terminal X2 and structure ground, with a 20 AWG ground wire with clip leads.

3.1 Hydraulic Systems

- Connect 28 VDC external ground power supply cart to aircraft. DO NOT TURN ON AT THIS TIME.

- Apply 25 PSIG air pressure to reservoir. Use nitrogen bottle with pressure regulators. (Furnished by Dept. 871)

  CAUTION: Operation of the 8000 psi motor/pump unit without engines running requires external reservoir pressurization. Apply air pressure through a capped tee located near the reservoir pressure regulator.

- Disconnect power plug from EDU Recept J4. Disconnect both connectors from the microcomputer Recepts J2 and J3. Connect plug to heat exchanger blower.

- Disconnect connector from microcomputer power supply.

- Apply 28 VDC to aircraft. Turn on #1 inverter. Heat exchanger blower should be running.

- Turn rudder hydraulic power switch "ON" in cockpit. Observe that pressure is 8000 psi on cockpit gage. Look for leaks (especially at actuator).

- Turn off rudder hydraulic power switch, #1 inverter and 28 VDC ground power supply.

3.2 Analog Back-Up Mode

- Connect J4 on the EDU to the A/C harness. Connect J3 on the EDU to the AFCAS test box provided by Dept. 871.

- Turn on 28 VDC ground power supply. Verify DFBW switch is "OFF".

- Turn #1 inverter "ON", then turn rudder hydraulic power switch "ON". Motor/pump should be running and EDU should be powered.

- Operate rudder pedals. Assure that operation is satisfactory. Rapidly oscillate rudder a sufficient number of cycles (at least 25) to remove any trapped air within the rudder actuator. Note sensitivity and dead band.

- Apply full right and left pedals. Measure and record rudder deflection. Maximum right and left rudder should be 12 $\pm$ 1/2 degree. Determine that rudder returns to 0 $\pm$ 3/4 degree with no pedal force.

- At the AFCAS Test Box, measure and record the voltages shown below with no rudder pedal command.

Description	Required Voltage
Actuator LVDT Output Voltage	0 $\pm$ 0.100 VDC
Force Transducer Output Voltage	0 $\pm$ 0.125 VDC
Valve Driver Output Voltage	0 $\pm$ 0.500 VDC

3.3 Digital Fly-By-Wire Mode

- Measure 115 VAC between pins K and L of μC Power Supply aircraft electrical connector.

- Place DFBW Engage switch to "ON" and hold.

- Check DFBW light illuminated.

- Measure 28 VDC between pins K(+) and L(-) of microcomputer aircraft electrical connector MS3116P-14-19S (J2).

- Release DFBW switch. Verify that toggle lever returns to "OFF" position and DFBW light is NOT illuminated.

- Turn rudder Hyd Pwr Sw "OFF".

- Connect microcomputer and associated power supply electrical connectors to appropriate receptacles.

- Turn rudder hydraulic power switch "ON".

- Operate rudder pedals. Assure that operation is satisfactory.

- Turn DFBW switch "ON". Observe that DFBW light is "ON".

- Operate rudder pedals. Assure that operation is satisfactory.

- Apply full right and left pedals. Measure and record rudder deflection. Maximum right and left rudder should be 12 ± 1/2 degrees. Determine that rudder returns to 0 ± 3/4 degree with no pedal force.

- Measure and record the voltages shown below with no rudder pedal command.

Description	Required Voltage
Actuator LVDT Output Voltage	0 ± 0.10 VDC
Force Transducer Output Voltage	0 ± 0.125 VDC
Valve Driver Output Voltage	0 ± 0.500 VDC

- Turn rudder hydraulic power switch "OFF". Verify that DFBW switch goes to "OFF" and DFBW light is not illuminated.

- Reengage rudder hydraulic power switch. Turn DFBW switch "ON".

- Cycle rudder pedals to ensure correct operation.

- With system operating, disconnect ground and jumper wire from Hydraulic Pump Motor Relay.

- Observe that DFBW system will monitor off (switch in "OFF" position) and DFBW light is not illuminated.

  NOTE: If system is perfectly nulled, it may not monitor off until a pedal input is applied.

- Turn rudder hydraulic power switch "OFF".

- Reconnect ground wire C237A20NT between Hydraulic Pump Motor Relay terminal X2 and structure ground.

- Turn rudder hydraulic power switch "ON".
- Verify hydraulic pump operation.
- Turn rudder hydraulic power switch "OFF".
- Turn #1 inverter "OFF" and remove external ground power.
- Remove jumper wires from #1 GBC Relay No. 3 socket and from #2 GBC Relay No. 3 socket and replace relays.

III. SYSTEM DESCRIPTION AND PILOT INFORMATION

Changes made to the aircraft to incorporate the Digital AFCAS are described herein. The test installation is a fully powered digitally controlled directional system with an analog control-by-wire back-up. The system contains:

- Electric Motor Drive Pump
- Rudder Actuator
- Electronic Drive Unit
- Digital Microcomputer
- Force Transducers
- Microcomputer Power Supply

The modified hydraulic system will operate at two pressure levels: 3000 psi and 8000 psi. An 8000 psi motor/pump unit has been added to power the rudder system (only). Both engines drive the normal 3000 psi pumps which power the lateral, horizontal, speed brake, and landing gear systems in the usual manner. The 3000 psi and 8000 psi systems have a common reservoir and common return lines. The modified system will operate functionally the same as the basic T-2C aircraft except the rudder will be hydraulically powered.

The original cable system between the rudder pedals and rudder has been modified to incorporate the control-by-wire system. The rudder pedal cables operate a sector which is prevented from rotating by a force transducer. The rudder pedals will have very little displacement. Force on the pedals is converted to a proportional electrical signal from the force transducer.

In the DFBW mode (DFBW switch "ON"), the electrical signals from the force transducers and rudder actuator LVDT's are sent to the microcomputer where they are amplified, summed, and converted into digital PWM signals. The PWM signals are transmitted to the EDU for power amplification and drive for the actuator torque motor. The torque motor drives the hydraulic control valve on the rudder actuator.

In the ABU mode (DFBW switch "OFF"), the force transducers and rudder actuator LVDT signals bypass the microcomputer, and are connected directly to the EDU where they are summed and power amplified to drive the actuator torque motor. The EDU contains redundant circuitry which provides immunity to system failures.

This system is illustrated in the system diagram of Figure C-1.Use of the microcomputer offers the opportunity of digitally processing additional signals that might be desirable. In this application the microcomputer is self-monitored. If improper DFBW mode operation is detected, the unit will disengage and return to the ABU mode. During normal system operation, the pilot should note little difference between the DFBW and the ABU mode of operation.

The rudder actuator has a pressure operated by-pass valve which permits the rudder to trail if hydraulic power is lost. In the event of a "hard over" type failure, the pilot can cause the rudder to trail by turning the 8000 psi rudder hydraulic power system switch to "OFF".

The rudder trim system is unchanged. Trim response will be different, however, due to the change from a manual to a fully powered rudder. The yaw damper system has been disconnected.

Maximum rudder displacement is reduced from ±25 degrees to ±12 degrees. This reduction will permit the pilot to land safely with a "hard over" rudder, opposite engine out, and a three knot cross wind. The relationship between rudder displacement and pedal force is approximately 7 lb/deg. of rudder movement (±84 lb. for full travel).

Because of the additional load imposed on the 28 VDC generators, the motor/pump unit can be operated only when both engines are running. For this reason, the unit can only be turned "ON" with both engines operating.

Modifications in the cockpit area are as follows:

1. 8000 psi hydraulic pressure on the rudder actuator and electric power to the EDU and microcomputer can be shut off by means of a rudder hydraulic power switch located on the pilot's auxiliary instrumentation control panel (shroud).

   NOTE: For total flight control boost shut-off, the above hydraulic power switch and the normal system boost shut-off switch must be moved to "OFF". The rudder will trail in this situation and cannot be operated.

2. Output from the 8000 psi pump is displayed on the upper right hand side of the pilot's instrument panel.

   NOTE: The pressure displayed is in the pump discharge line and will fall to zero when the hydraulic power switch is at "OFF".

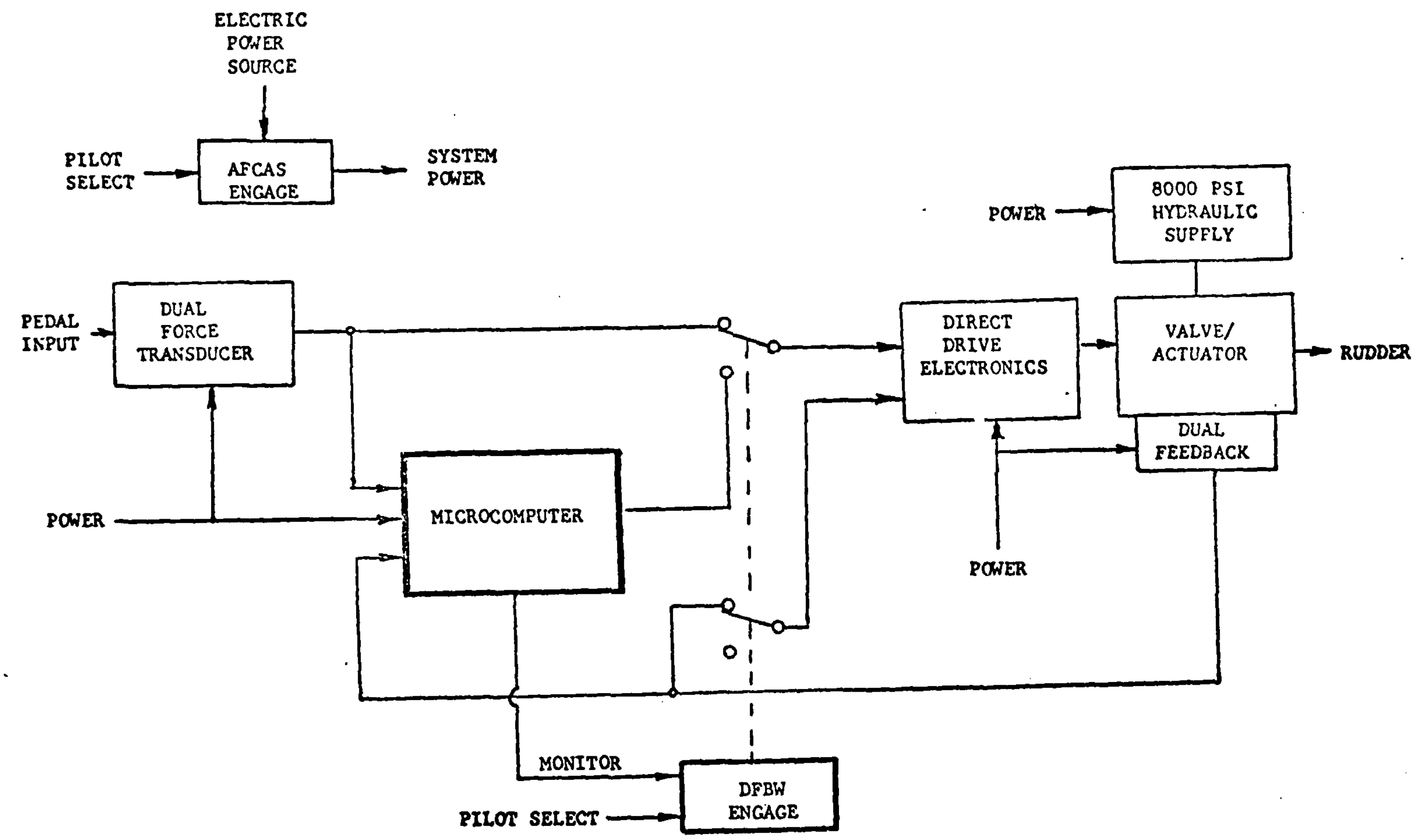

Figure C-1 Digital Fly-By-Wire AFCAS System Block Diagram

3. An "oil hot" light has been provided on the pilot's auxiliary instrument panel (shroud). This light indicates excessive hydraulic system oil temperature. Actuation of the light is an indication of system malfunction.

4. The DFBW switch, located on the pilot's auxiliary instrumentation control panel, operates the microcomputer. When the microcomputer is operating, the indicator light will be "ON". When the indicator light is extinguished, the system will be operating in the ABU mode.

Contingency recommendations are:

1. DFBW Switch "ON", Hydraulic Power Switch "ON"

   (a) If left and right yaw responses become significantly different or erratic, turn DFBW switch "OFF".

   (b) If rudder becomes "hard over", turn DFBW switch "OFF".

2. DFBW Switch "OFF", Hydraulic Power Switch "ON"

   (a) If the left and right yaw responses become significantly different for equal inputs, a malfunction in the system is indicated. Terminate test. Turn the rudder hydraulic power switch "OFF" and use a low power setting for the return flight.

   (b) If the rudder should become "hard over", terminate test. Turn rudder hydraulic power switch "OFF" and use a low power setting for the return flight.

3. If the "oil hot" light comes on, terminate test. Turn rudder hydraulic power switch "OFF". Reduce power setting and alternately cycle the speed brakes and landing gear during return flight to lower bulk fluid temperature. Stop cycling when fluid temperatures become normal.

4. If the 8000 psi system pressure drops below 6000 psi, terminate test. Turn the rudder hydraulic power switch "OFF" and use a low power setting for the return flight.

5. If it should become necessary to shut-down one engine, turn the rudder hydraulic power switch "OFF" before engine shut-down.

   NOTE: Shut-down of one engine will cause loss of 8000 psi hydraulic power.

IV. FLIGHT TEST PROCEDURE

FIRST FLIGHT

GOAL - Functional check DFBW operation in flight, and to acquire flight time on the system.

MAXIMUM ALTITUDE - 20,000 feet

MAXIMUM SPEED - 250 KOAS

PILOT CHECKOUT - With engine operating and normal electrical power, turn hydraulic power switch "ON".

- Check rudder system by cycling pedals and observing normal rudder operation.
- With instrumentation "ON", ensure DFBW engage switch is "OFF".
- Check rudder system by cycling pedals and observing normal rudder operation.

TAKEOFF - Record data continuously during first one minute of takeoff and climb.

PILOT MANEUVERS -

NOTE: Pilot to perform these at his discretion. Recorders "ON". Pilot to comment after landing. DFBW switch "ON".

- Apply small rudder inputs, note response and dead band.
- Apply pulse inputs, evaluate recentering, left and right.
- Make comparison of DFBW "feel" with ABU "feel".
- Comment on rudder pedal operation, i.e., no displacement (force only).
- The pilot is encouraged to perform any additional maneuvers that would provide worthwhile data. Maneuvers that could result in dynamic overswing conditions are prohibited.
- Perform large side slip maneuvers left and right up to 1/2 directional control if possible.

LANDING - Record data continuously during the minute prior to touchdown.

POST FLIGHT -

- De-brief pilot after each flight. Pilot comments to be correlated with maneuvers and instrumentation correlator and markers.
- Copy of flight card with instrumentation correlation and pilot comments made available to Dept. 71.
- Copy of recorded data made available to Dept. 71.
- Make decisions regarding changes or additional procedure for next flight.

SECOND FLIGHT

GOAL - Compare DFBW mode with ABU mode; acquire operational flight time on DFBW system.

MAXIMUM ALTITUDE - 20,000 feet

MAXIMUM SPEED - 250 knots

PILOT CHECKOUT - Same as flight one.

TAKEOFF - Same as flight one.

PILOT MANEUVERS -

- Pilot to verify system operation with DFBW switch "ON".
- Place DFBW engage switch "OFF", verify directional control with ABU system. (Slight trim changes may be present when switching, observe direction and magnitude of transient.)

NOTE: Pilot to perform these maneuvers with the DFBW switch alternately "ON" and "OFF" and to compare performance. Recorders "ON" for maneuvers. Pilot to comment on performance.

- Apply small rudder inputs, note response and dead band.
- Apply pulse inputs, evaluate recentering, left and right.
- Make comparison of DFBW"feel" with ABU "feel".

- Comment on rudder pedal operation, i.e., no displacement (force only).
- The pilot is encouraged to perform any additional maneuvers that would provide worthwhile data.

LANDING - Same as flight one.

POST FLIGHT - Same as after flight one.

THIRD FLIGHT

GOAL - Acquire additional flight time on DFBW control, repeat data points from first two flights as required.

ALTITUDE - Sea Level to 30,000 feet

AIRSPEED - Up to 340 KOAS or 0.7 MN, whichever is less

PILOT CHECKOUT - Same as flight one.

TAKEOFF - Same as flight one.

PILOT MANEUVERS - Optional, dynamic overswing maneuvers are prohibited.

LANDING - Same as flight one.

POST FLIGHT - Same as flight one.

V. FLIGHT INSTRUMENTATION

The following is a list of the instrumentation planned for the flight tests. Some parameters may be substituted if laboratory tests or first flight tests indicate a need to change instrumentation.

PHOTO RECORDER SYSTEM

PARAMETER	RANGE	ACCURACY	READOUT RESPONSE
1. Time	N/A		
2. Airspeed	50 to 500 kts (26 to 250 m/s)		
3. Altitude	0 to 50,000 ft. (15.2 km)		
4. RPM, L/R Engines	0 to 8,000 RPM		
5. Fuel Counters, L/R Engines	N/A		
6. Correlation and Pilot Marker	N/A		
AFCAS Parameters			
7. Flow, Pump Case Drain Line	0 to 1.0 GPM (0 to 3.7 L/m)	±2%	2 Hz
8. Flow, Pump Suction Line	0 to 1.0 GPM (0 to 3.78 L/m)	±2%	2 Hz
9. Temp, EDU Housing	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
10. Temp, Fuselage Compartment Air	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
11. Temp, Pump Suction Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
12. Temp, Pump Case Drain Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
13. Temp, Heat Exchanger Inlet Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz
14. Temp, Heat Exchanger Outlet Fluid	-50 to +350°F (-46 to +177°C)	±3%	2 Hz

TELEMETRY SYSTEM

PARAMETER	RANGE	ACCURACY	READOUT RESPONSE
1. Correlation and Pilot Marker	N/A		
2. Temp, Outside Air	-76 to +140°F (±60°C)		
3. Acceleration, Normal (Vertical)	-5 to +10g		
AFCAS Parameters			
4. Press, Pump Suction Line	0 to 50 psia (0 to .3 MPa)	±3%	100 Hz
5. Press, Pump Discharge Line	0 to 10,000 psig (0 to 69 MPa)	±3%	100 Hz
6. Press, Pump Case Drain Line	0 to 100 psia (0 to .6 MPa)	±3%	100 Hz
7. Position, Rudder	±12°	±2%	100 Hz
8. Position, AFCAS Transducer #1	±10 volts DC	±2%	100 Hz
9. Position, AFCAS Transducer #2	±10 volts DC	±2%	100 Hz
10. Force, AFCAS Transducer #1	±2.5 volts DC	±2%	100 Hz
11. Force, AFCAS Transducer #2	±2.5 volts DC	±2%	100 Hz
12. Current, AFCAS Motor Coil #1	±1.0 volts DC	±2%	100 Hz
13. Current, AFCAS Motor Coil #2	±1.0 volts DC	±2%	100 Hz
14. Current, AFCAS Motor Coil #3	±1.0 volts DC	±2%	100 Hz
15. Current, AFCAS Motor Coil #4	±1.0 volts DC	±2%	100 Hz
16. Temp, Oil Hot Light (+200°F)	N/A		

VI. REFERENCES

(1) NAVAIRDEVCEN 75287-60, Flight Verification of the Advanced Flight Control Actuation System (AFCAS) in the T-2C Aircraft, dated June 1978.

(2) 78CL 2503, Installation of a Computer in the T-2C Test Aircraft Equipped with AFCAS, Integrated Test Plan, dated 22 December 1978.

APPENDIX D

RELATED ELECTRONIC INTERFACE STUDIES PULSE MODULATED DRIVE CONCEPTS

(SUMMARY OF COMPANY FUNDED IR&D PROJECTS)

In advanced aircraft using digital fly-by-wire control, direct-drive actuators show considerable advantages because of their ruggedness, relative simplicity and high reliability. Both the Navy and Air Force have research programs under way to develop direct drive actuation.

Previous work on this project has demonstrated that low level analog signals, such as are provided by a D/A converter, can be suitably amplified into the higher power forms required for closed loop control. Analog valve drivers, using quadruple redundancy and optimized for linear (Class A) operation, were successfully tested and demonstrated in the laboratory. A modified PDP-11 minicomputer with built-in A/D and D/A converters was used to close the loop both internal and external to the minicomputer. Flightworthy analog valve drivers were developed with IR&D funds. This design was fabricated and flown under Phase V of the AFCAS program.

Following Phase V, additional IR&D research was conducted to develop an approach that would (1) eliminate the need for D/A and A/D converters and (2) reduce the cooling requirements of the drive amplifiers.

Experiments were performed using error signals in various pulsed formats including "bang-bang" pulse width modulation and time dwell modulation.

The use of pulsed drive waveforms offers several potential advantages:

- D/A converters are not needed, since digital circuitry can generate the pulsed waveforms.

- A/D converters for "wrap-around" monitoring are not needed.

- Pulsed waveforms allow the valve driver amplifiers to act as switches rather than as linear amplifiers. As a result, the power dissipation in the drive transistors can be reduced by a factor of 10 or more, thereby improving the reliability and reducing the weight of the drivers and power supplies. The overall efficiency of the DFBW system is also improved as a result of the lower power dissipation.

- Dynamic pulsed waveforms are compatible with passive fault isolation schemes whereby a hardover computer output can be blocked without the need for a disconnect arrangement.

The results were sufficiently encouraging to warrant investigations into a new digital valve driver amplifier concept better suited to pulsed waveforms than are the linear analog drivers, and designed to exploit the potential advantages offered by the use of pulsed waveforms in aircraft having several actuation systems under direct digital control.

The digital drive concept, illustrated in Figure D-1,was constructed and tested. The typical waveforms are illustrated in Figure D-2. The circuit incorporates two features which reduce the size and weight over that of an analog drive. First, the transistors operate in a switching mode to reduce the internal power dissipation. Second, the circuit is designed to operate from a single polarity power supply.

In addition the circuit can be designed for dynamic operation, that is, a pulse rate is required to obtain an output. The absence of pulses results in zero output. If some form of AC coupling is provided between the computers and the power amplifier, a hardover failure of a computer output circuit would result in a passive failure and not a hardover failure. This permits the computers to perform self-monitoring and remove themselves from the line if a failure occurs. It does not matter if the computer output is zero or a plus voltage,it is still removed from the drive. This provides opportunities for many forms of redundancy in the actuator drive.

The breadboard digital driver was tested as a part of the closed loop system. A direct drive torque motor was used to provide a realistic load for the driver. A simulated actuator was configured to enable studying the dynamic response of the loop, which was closed by the computer. The computer generated the "surface error signal" in the pulse modulation format. The following specific results were achieved:

1. The circuit concept was verified and a data base was established for use in optimizing future operational circuit designs.

2. The closed loop test results showed that the desired closed loop frequency response can be obtained with proper compensation for the inductive characteristics of the valve coil.

3. The qualitative effects of pulsed waveforms on the torque motor were evaluated and found to have little effect on the motor when operated at frequencies above 500 Hz.

The closed loop frequency response without any form of compensation is shown in Figure D-3. With computer compensation this bandwidth can be extended for small signals (1% of full travel) by a factor of 4 to about 26 Hz. This is illustrated in Figure D-4.

For certain dynamic situations, large changes in the surface displacement would be desired requiring increased bandwidth for large signals.

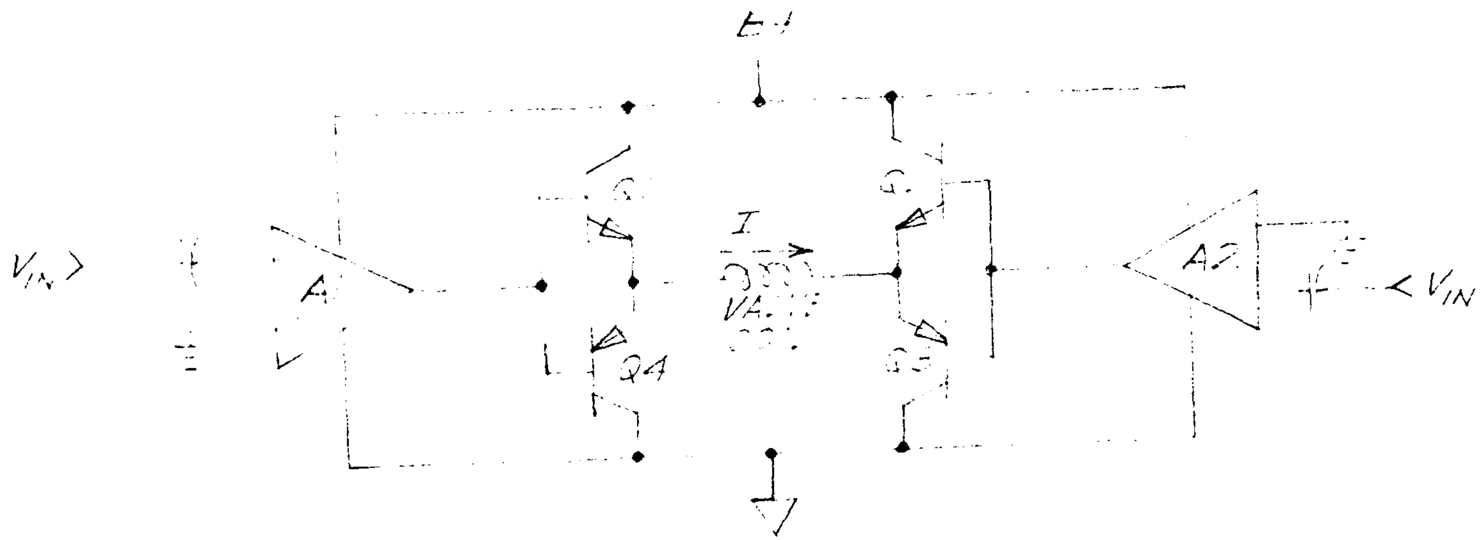

Figure D-1 Digital Drive Unit Concept

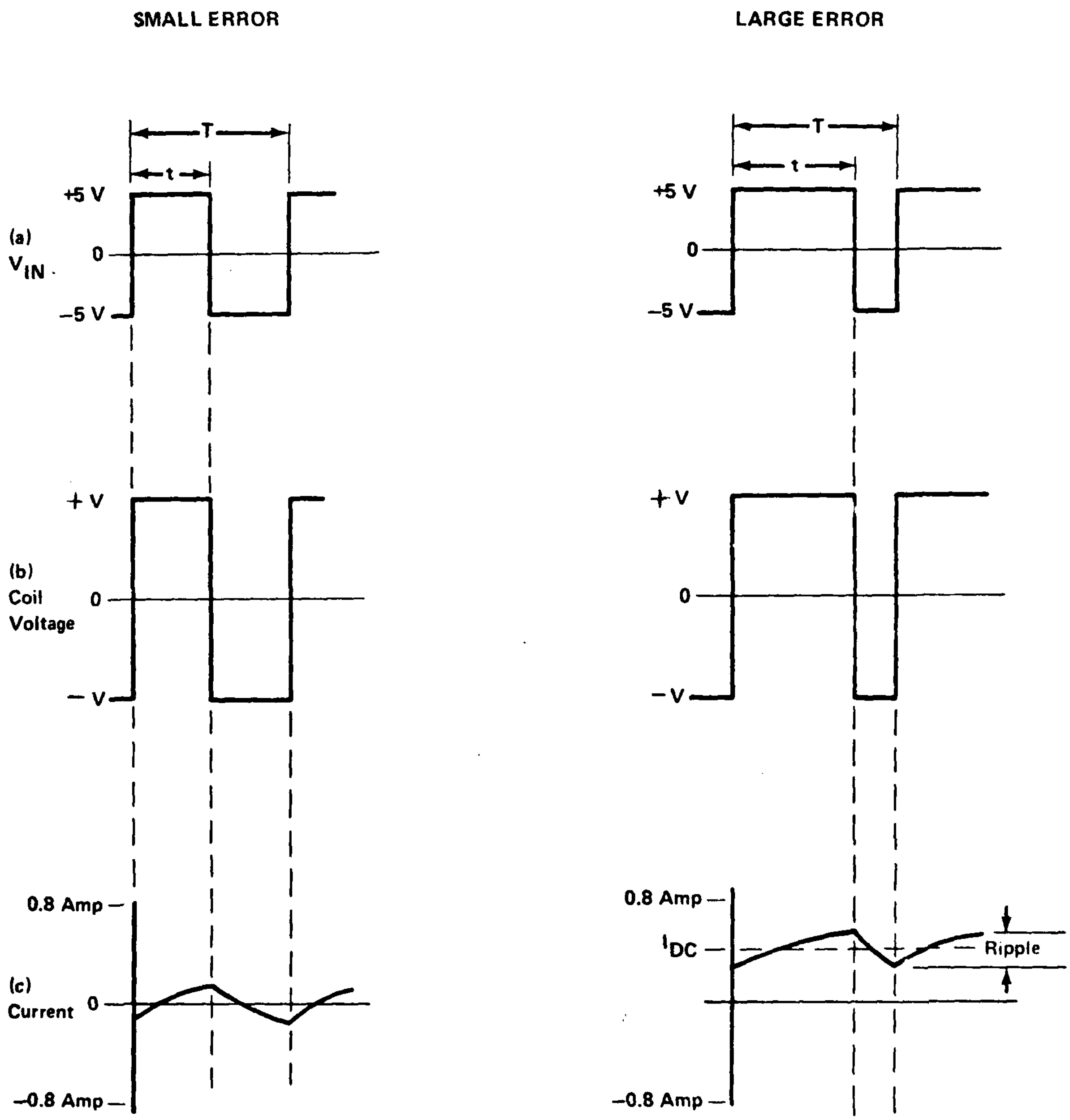

Figure D-2 Digital Drive Concept Waveforms

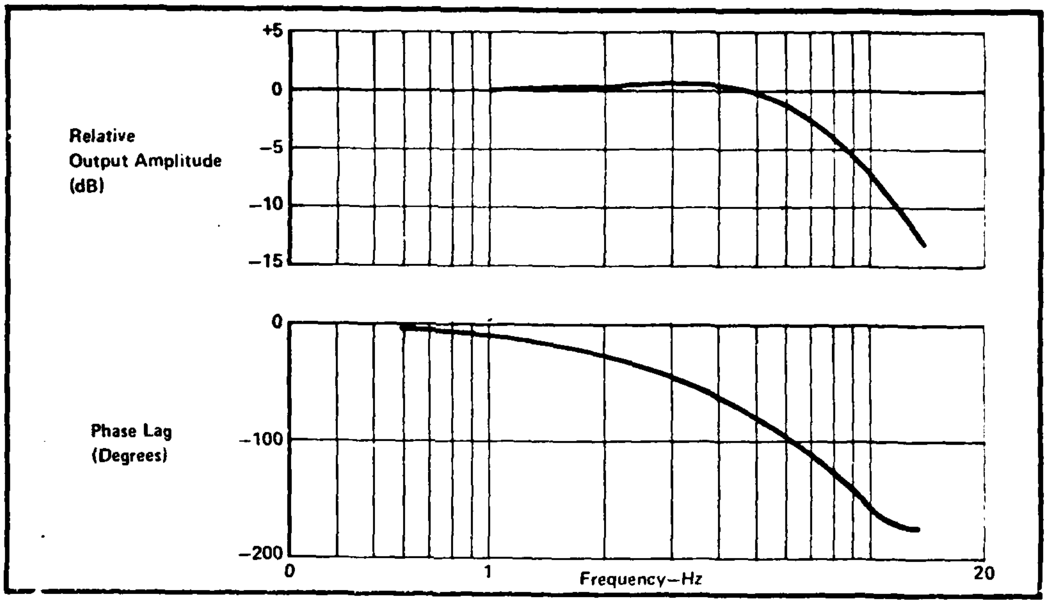

Figure D-3 Closed Loop Response (Uncompensated)

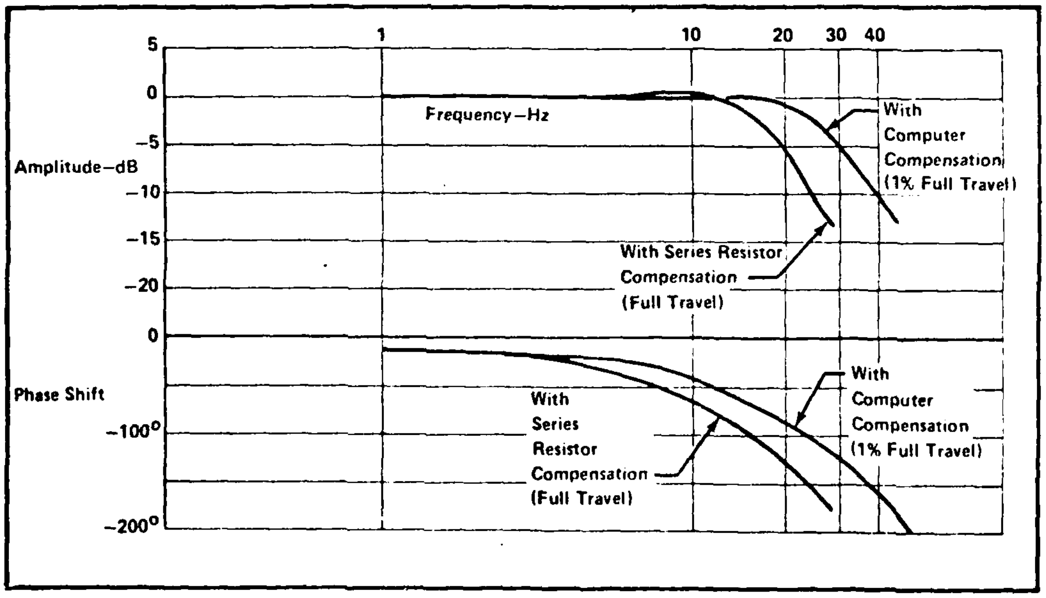

Figure D-4 Effect of Compensation Method on Closed Loop Response

Resistance in series with the motor coil is the simplest, most effective means of providing the needed compensation. The resultant large stroke response is shown in Figure D-4. This method also offers the advantage of maintaining valve driver power bandwidth over the full range of error signal levels - that is, the large signal response is identical with the small signal response. The closed loop bandwidth will be limited only by the rate capacity of the actuator itself. The use of a series resistor provides an additional advantage of current-limiting protection in the event of a hardover failure.

This work, performed under company IR&D funds, demonstrated a method to take maximum advantage of pulse modulated control. While pulse modulation performs satisfactorily with analog (Class A) amplifiers, the use of drive circuits designed especially for pulse modulation produces a significant reduction in size and power (heating) dissipation in the drive circuit. Because of the low power dissipation of the electronics, the temperature rise is slight and the electronics could be packaged directly into the surface actuator. A direct drive actuator design that utilizes electronics of this type integrated into the actuator has been developed by Rockwell.

LIST OF ABBREVIATIONS/ACRONYMS

AC	Alternating Current
ABU	Analog Back-Up
ACIA	Asynchronous Interface Adapter
A/D	Analog to Digital
AFCAS	Advanced Flight Control Actuation System
Amp	Ampere
AROM	Alterable Read Only Memory
Aux	Auxiliary
°C	Degrees Celsius
cc/min	cubic centimeters per minute
c	centi (10^{-2})
cm^3	cubic centimeters
CMD	Pilot Command
CPU	Central Processing Unit
D/A	Digital to Analog
DAC	Digital to Analog Converter
db	decibel
DC	direct current
deg	degree
DFBW	Digital Fly-By-Wire
DVM	Digital Voltmeter
EDU	Electronic Drive Unit
°F	degrees Fahrenheit
FRP	Flight Reference Plane

FUS STA	fuselage station
ft	feet
F/T	force transducer
ft/sec	feet per second
gpm	gallons per minute
HOFCAS	Hydra-Optic Flight Control Actuation System
hp	horsepower
H_p	pressure altitude (29.91 in. Hg = Sea Level)
Hz	Hertz (cycles per second)
in.	inch
in^2	square inches
in^3	cubic inches
INST	instrument
I/O	input/output
k	kilo (10^3)
kg	kilogram
km	kilometer
KOAS	Knots Observed Airspeed (uncorrected)
kW	kilowatt
lb	pound
L	liter
LED	light emitting diode
L/m	liters per minute
LHS	Lightweight Hydraulic System
LVDT	Linear Variable Differential Transformer
m	meter, also milli (10^{-3}), also minute
M	mega (10^6)

max	maximum
mm	Millimeter
M/N	model number
min	minute (time)
MPa	megapascals
MPU	Microprocessing Unit
m/s	meters per second
mv	millivolt
N	Newton (metric unit of force)
NAAD-C	North American Aircraft Division - Columbus
NADC	Naval Air Development Center
No.	Number
OAT	outside air temperature
P-P	peak-to-peak
ΔP	differential pressure
Pa	pascal (metric unit of pressure)
pk to pk	peak to peak
PIA	Peripheral Interface Adapter
POS	rudder position
PROM	Programmable Read Only Memory
psi	pounds per square inch
psia	pounds per square inch absolute pressure
psig	pounds per square inch gauge pressure
PM	pulse modulation
P/N	part number
PWM	pulse width modulated
RAM	Random Access Memory

R&D	Research and Development
RH, R/H	right hand
ROM	Read Only Memory
rpm	revolutions per minute
s	second (time), also LaPlace transform operator
sec	second (time)
SL	sea level
TM	telemetry
T/O	take-off
UHF	ultra-high frequency
V	volt
VDC	volts direct current
W	watt
W.L.	water line
XDCR	transducer
XFMR	transformer

SUMMARY OF METRIC CONVERSIONS

Area	in^2	x	6.452	=	cm^2
	ft^2	x	.0929	=	m^2
Fluid Flow	gal/min	x	3785	=	cc/min
	gal/min	x	3.785	=	L/min
	in^3/sec	x	16.39	=	cc/sec
Force	lb	x	4.448	=	N
Length	in	x	2.540	=	cm
	ft	x	.3048	=	m
Mass	lb	x	.4536	=	kg
Pressure, Stress	psi	x	6895	=	Pa ($=N/m^2$)
	psi	x	.06895	=	bar
Velocity, Speed	in/sec	x	2.540	=	cm/sec
	ft/sec	x	.3048	=	m/sec
	knots	x	.5144	=	m/sec
Volume	in^3	x	16.39	=	cm^3 (-cc)
	gal	x	3.785	=	L
	l	x	1000	=	cm^3
	m^3	x	1000	=	L